A Robust and Optimal Multidisciplinary Approach For Space Systems Conceptual Design

Doctoral Dissertation
Doctoral Program in Aerospace Engineering (31th Cycle)

A Robust and Optimal Multidisciplinary Approach For Space Systems Conceptual Design

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Politecnico di Torino
June 30th, 2019

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Torino, April 19th, 2019

Summary

Modern approaches to space project management and execution aim at assuring the harmonic balance of interests, since space projects are always more and more value-oriented and cost-constrained. The management of stakeholders' needs, project schedule and requirements constitute the pillars for the success of a space programme. The current approach of space industry to the Space 4.0 era pushes the space mission design process towards a multi-stakeholder environment. The increased number of stakeholders and interconnections among them, together with their different and complex needs, increase the complexity of the design process, mainly in the early phases of the mission lifecycle.

It is necessary/fundamental to have a clear definition of the problem under analysis, especially when dealing with the initial problem definition. State of the art shows that more detailed definition can be robustly obtained thanks to the generation and exploration of design alternatives with respect to social accepted figure of merits. Nonetheless, it is necessary that this process considers that the design involves various individuals, who take decisions affecting one another. Currently, the most promising design approach for dealing with multi-stakeholder scenarios is offered by Concurrent Engineering. In this approach, the complete design team, composed of technical domain specialists and principal investigator, starts working in a quasi-parallel execution on different aspects of the project, already at the beginning of the design process.

Taking full advantage of concurrent engineering approach and with the goal of enhancing the benefits provided by the approach itself, this doctoral research developed a concurrent design methodology which aims to speed up and enhance the effectiveness of space missions conceptual design.

The developed methodology, named *Multi stakehOlder NEgoTiation space exploration (MONET)* encompasses two principal phases: a preliminary concurrent engineering study and a follow-up concurrent engineering session. In the concurrent engineering study, the methodology assists system engineers and, more in general, stakeholders with the generation and exploration of several design alternatives through the so-called negotiation space.

The proposed methodology emulates a collaborative game, in which the negotiation among stakeholders can be optimized in order to balance all the needs and to reduce the design iterations needed to satisfy all the different and complex needs involved in the project, aiming to the maximization of both team social welfare and single stakeholders perceived utility.

Once a reduced set of optimal negotiated designs is selected, each design is then analysed in more details during the concurrent design session. In order to assist the engineers during the concurrent design sessions, the methodology includes an harmonic integration of artificial intelligence (AI) in the form of knowledge based expert systems. To highlight the benefits of the proposed methodology, the thesis presents the design of a CubeSat mission for the observation of Lunar radiation environment as test case. Results show that the methodology ensures inter-compatibility and satisfaction among stakeholders while guaranteeing the technical feasibility of the negotiated design.

The methodology results suitable to handle multi-stakeholder problems at system level and, at the state of the art, provides support to the engineering team in the decision-making process, including:

1) novel technologies, such as AI-based techniques and methods, e.g. multi disciplinary optimization (MDO) for tradespace exploration, integrated into a single environment.

2) standardisation of session objectives and execution, i.e. application of concept maturity level.

3) first iteration of integration of Virtual Reality. Further development in this direction is seen as a possible improvement of any concurrent design environment.

The complete methodology has been implemented into a Concurrent Engineering Facility (CEF) at Politecnico di Torino. A tailored methodology concerning system and mission adaptable design tools, have been developed, updated and validated throughout their applications on different CEF mission studies.

To this respect, the CEF has been successfully used in the first European Concurrent Engineering Challenge organised by ESA in 2017.

Acknowledgment

The first acknowledgment must go to my raison d'etre and my hero: my mom. You have been perfect till the end. I owe my life to you…I mean for real. We will fight together forever!

To my life-coaches and supporters, my dad, grandparents and Mary: because I owe it all to you. Many Thanks!

My eternal cheerleaders and life coaches as well: Raffaele , my sister Martina, my brothers Lorenzo & Daniele: I miss our "*interesting and long-lasting chat*". I am who I am thanks to you…I owe all since 6 "Super" years of my life at least.

I am incredibly grateful to Sofia and her parents, whose have provided me through moral, emotional and life support throughout these last years at best. Thank you so much <3 .

A composed and regal acknowledgment to my academic tutor and lovely aunt Sabrina that always believed in me giving me the chance to challenge myself with adventure called PhD. You teach me a lot, you let me become the engineer and researcher that I am, I owe you so much. A technical and "controlled" thank you to Fabrizio. A last academic acknowledgment must go to Paolo Maggiore, my academic "dad" that supported me since my bachelor defence. A thank you also to my referees that gave their time in reviewing my manuscript. A very special gratitude goes out to all down at STARLab and office friends. Andrea (we will see again as colleagues you frisking freak), Carlo, Christopher (It has been an honour be the first man to now everything), Davide, Roberta, Valeria, Gabriele, Lorenzo, L.A.L.L.A. To all the students of the CubeSat team and the course of space mission and system design, some of them I can now call friends. A special thanks must go to Natacha, Joost, Viyas, David and the whole ESA academy team. It is a pleasure to call you colleagues and friends. To my Belgian family Sophie and Maxime. Special mention and acknowledgement to everyone that supported me and changed my life towards a better future, Alice (I owe you a lot as well) Christian, Alessio.

And finally, last but by no means least, also to everyone that have been/are part of my life (e.g. the whole Turin gang) and I've forgot in this very hard duty of writing acknowledgments in 1 page….."Gentlemen, it has been a pleasure playing with you tonight"

Thanks for all your encouragement!

To my family, to everyone that supported me writing my story.
To the monster inside me that tries to defeat me

To my mom, the woman of my life:

"Ho sceso, dandoti il braccio, almeno un milione di scale e ora che non ci sei è il vuoto ad ogni gradino. Anche così è stato breve il nostro lungo viaggio. Il mio dura tuttora, nè più mi occorrono le coincidenze, le prenotazioni, le trappole, gli scorni di chi crede che la realtà sia quella che si vede.

Ho sceso milioni di scale dandoti il braccio non già perché con quattr'occhi forse si vede di più. Con te le ho scese perché sapevo che di noi due le sole vere pupille, sebbene tanto offuscate, erano le tue."

- *Eugenio Montale – Milano, Mondadori 1971*

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Acronyms

A

ADCS	Attitude Determination and Control System
AI	Artificial Intelligence

C

CD	Concurrent Design
CDF	Concurrent Design Facility
CEF	Concurrent Engineering Facility
CML	Concept Maturity Level
CO	Collaborative Optimization
CRM	Concurrent Requirements Modelling

D

DHS	Data Handling System
DM	Decision Maker
DMC	Discipline Maturity Chart

E

ECSS	European Cooperation for Space Standardization
EPS	Electrical Power system
ES	Expert System
ESA	European Space Agency

F

FFG	Österreichische Forschungsförderungsgesellschaft (Austrian Research Promotion Agency)

G

GA	Genetic Algorithm

I

IOT	Internet of Things
ISO	International Organization for Standardization

J

JPL	Jet Propulsion Laboratory

K

KB	Knowledge Based

KBS	Knowledge Based Systems
L	
LEAG	Lunar Exploration Analysis Group
LEO	Low Earth Orbit
LEP	Lottery Equivalent Probability
LRO	Lunar Reconnaissance Orbiter
M	
MATE	Multi Attribute Tradespace Exploration
MAUT	Multi Attribute Utility Theory
MBSE	Model Based Systems Engineering
MDO	MultiDisciplinary Optimization
MONET	Multistakeholder NegotiatiOn space ExploraTion
N	
NASA	National Aeronautics and Space Administration
O	
OCDT	Open Concurrent Design Tool
P	
PM	Project Management
PPT	Peak Power Tracking
R	
ROI	Return Of Investment
S	
SE	Systems Engineering
SRL	Science Readiness Level
STM	Science Traceability Matrix
T	
TRL	Technology Readiness Level
TSE	TradeSpace Exploration
TT&C	Telemetry Tracking and control
V	
VR	Virtual Reality

Introduction

"Whatever the mind of man can conceive and believe, it can achieve."
Napoleon Hill

History of space exploration pictures the modern history of human begins. Enhancing themselves, discovering new frontiers and challenges, and building a worldwide collaboration in order to reach a common objective.

Hermann Ganswindt (1856–1934), born in Seeburg, East Prussia, can be considered as one of the pioneers of the space flight. Ganswindt was confident about the technical feasibility and realisms of a spacecraft. He also presented an elaborate functional and physical scratch to prove the actual feasibility of his idea. He presented publicly on May 27, 1891 at the Berlin Philharmonie his concept of a "*worldcraft*", theorizing how propulsion fundamentals could enable human space missions.

Nowadays, these concepts have become reality, thanks to engineers and scientist who were actual innovators for their time. Among them, Konstantin E. Tsiolkovsky (1857–1935) is considered the "father of cosmonautics" in Russia while Robert H. Goddard (1882–1945) is considered as the "father of rocket technology". Hermann Oberth (1894–1989) can be seen as a "pioneer of space flight" in Europe, while Wernher von Braun (1912–1977), who was his best student, surely did a disruptive innovation as well.

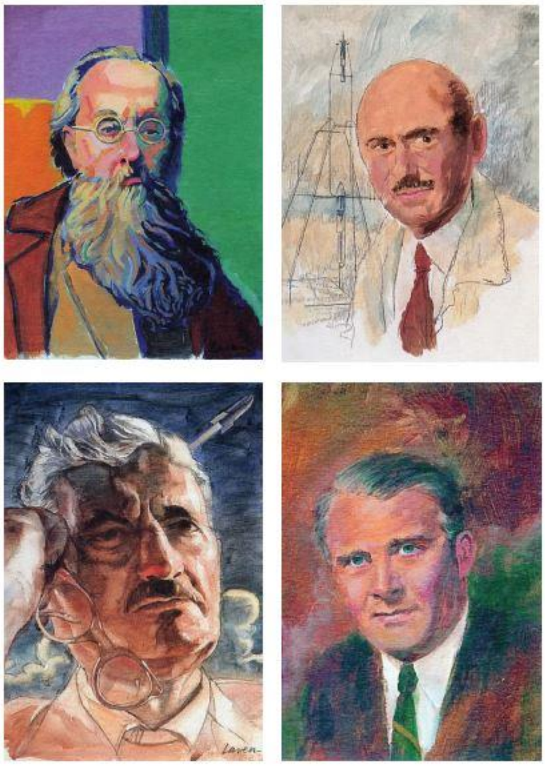

Figure 1 Portraits of space flight pioneers: Tsiolkovsky (top left), Goddard (top right), Oberth (bottom left) and von Braun (lower right) [1]

The basic concepts of modern space missions was developed in the years from 1935 to 1955 in which, engineering development was stimulated by war, first by World War II and then by the Cold War [1].

The official kick-off of space flight missions began in 1957, when an aluminium sphere, namely Sputnik, with a mass of 83 kg and a diameter of 58 cm, surprised and inspired the world (Figure 2). Today, after more than 50 years of history, space flight is not questioned by anyone.

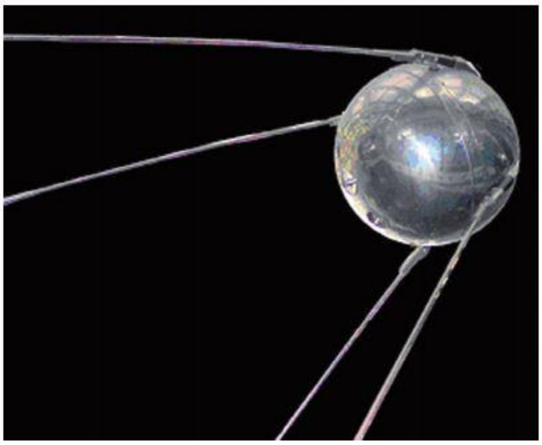

Figure 2 With the launch of the first artificial satellite Sputnik 1 on October 1957 the soviet uninion also launched the space age (source:ESA)

Afterwards, the technology development of human space flight in the last 50 years has experienced an incredible push. Russia has developed a deep expertise of low-Earth orbital flight with the Soyuz spacecraft, which has been operational from over 40 years. On the other hand, US has failed to effectively construct the basis for innovative human space flight technology, considering the meagre safety-record of the Shuttle Orbiter. However, US has a significant level of mastery of spacecraft technology thanks to the great success of the Apollo Era, which paved the way to the present space exploration programme. Moreover, China, exploiting the Soyuz heritage, was the third nation to develop an independent human space flight program in 2003.[1]

On the other hand, European space programs are mainly focused in the areas of astronomy, Earth observation, navigation, communications and exploration of the planetary system. With the European Galileo satellite navigation system, European Space Agency (ESA) is committed in a program of noticeable significance. Implementing this global navigation system calls for an extensive commitment of public and industrial actors in Europe. Only after humanity has mastered the technology of low-Earth orbit, it can consider moving beyond this, following the so called “global exploration roadmap”[2]. Indeed, in a memorandum from Robert S. McNamara, the then US Defense Secretary, and James E. Webb, the then NASA administrator, to Vice President Lyndon B. Johnson, dated May 8, 1961, 17 days before Kennedy announced the Apollo program to the US Congress, it was argued that achievements in space:

“symbolize the technological power and organizing capacity of a nation”[3]

Hence, it must be recognized that the romanticism of human space flight, along with the perceived national prestige, have held, and will continue to hold, the interest of politicians, securing funding for engineering, science, mathematics within both research and educational programs. Figure 3 summarizes the incredible journey that space exploration was and will be. Human begins will never stop to dream about space exploration pushing technology towards its limits.

With a great hope, this research is aimed to assist young and expert engineers towards the fulfilment of our “common dreams”.

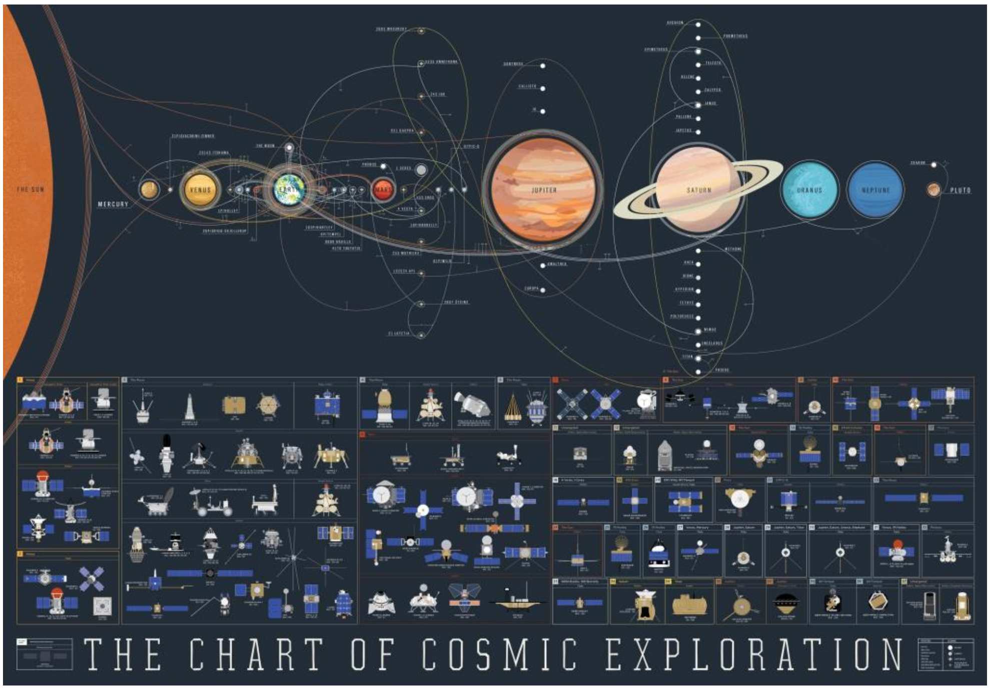

Figure 3 Chart of cosmic exploration (credits: http://tiny.cc/rjmq5y).

Chapter 1

Research context and methods

"*For me context is the key, from that comes the understanding of everything.*"
Kenneth Noland (1924 - 2010), American painter

This first chapter aims to give the context in which this research has been carried out. Particular attention will be given to standards, challenges and new trends within space mission design.

1.1 The space mission design process

"*Quality is never an accident: It is always the result of intelligent effort.*"
John Ruskin (1819–1900), British philosopher

A typical space mission is composed by three segments, which are designed, interfaced and operated in order to fulfil the mission objectives. Designing the mission segments and their mutual dependencies is the principal challenge for effectively developing and executing space missions.

The **space segment** includes the *spacecraft* and its *payload* in *orbit*. The **transfer segment** serves the transportation of the spacecraft and its payload into orbit by a *launcher* (typically a rocket) from a *launch site*. Last but not least, with the goal of controlling and monitoring the spacecraft and its payload and to analyse and share the payload data, a **ground segment** is required. The design drivers of ground and transfer segments design are function of the physical parameters of the spacecraft and the payload, which depend essentially on the mission objective and the mission duration.

The three cited mission segments can be further subdivided into the so-called system elements as *mission subject*, *space bus, payload, orbit, launcher, launch site, operations, ground stations and networks, mission products*.[1]

One of the central points to obtain an effective space mission is given by the management of the activities needed to properly develop and execute the mission. Throughout the history of space flight, tasks and processes necessary for the development of a space programs have been carefully elaborated. Today, space industry can exploit a consolidated experience, documented in several international and industrial standards. It is valuable to notice how the accomplishment of past space missions was oriented along technology path and performance values, whereas nowadays gain is more and more measured by profit considerations and value for money. This makes evident that the expectations of a space mission are no longer limited to the fulfilment of technical and scientific requirements.

Due to constrained budgets of public authorities, consumers, agencies and institutions, one essential driver of a space program and its management approach is addressed to accomplishing the project goals within the required time and budget.

Summarizing, programs in the space business are characterized by the following aspects, as highlighted in [1]:

- Uniqueness of the implementation approach;
- Time limitations;
- Limited resources;
- Political goals;
- Risky processes;
- Intercultural and multicultural cooperation;
- Interdisciplinary challenges;
- Highly complex requirements and tasks.

The success criteria of a space program, such as schedule, cost and quality, are influenced by the tasks to-be-fulfilled, and the size and complexity of the space mission. The conflict between the need for detailed planning and the tailoring of needs can only be solved by the application of systematic methods depending on the attribute of the project or the nature of the product. Typically, viewing a project from the “working point of view”, the so-called *topdown* approach is used for planning the whole life-cycle of the mission.

Generally, a space project may be either a procurement or a development program. Procurement programs are characterized by the exploitation of commercially-available and space-qualified items and processes with adequate heritage of their functionality in space missions. On the other hand, development programs may require additional process steps and effort due to the development and manufacturing of satellites with new technologies or new functional performance.

All processes from mission definition to system operation are subject to a common logic, which may be seen as a systematic approach presented in Figure 4.

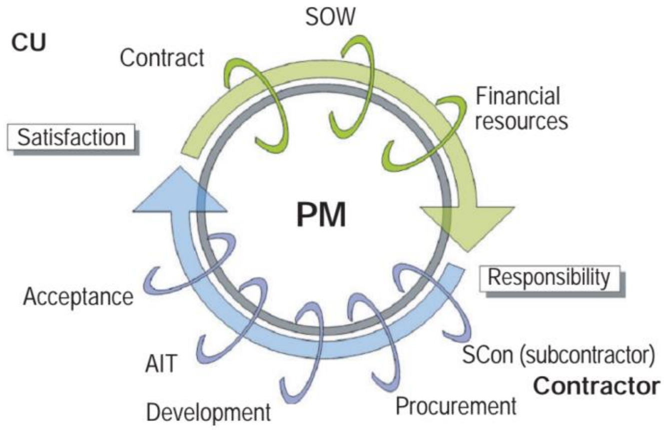

Figure 4 Quality-oriented process [1]

Modern quality management approaches are aimed to assures a balance of interests in successful projects. Indeed, this balance is very important for the following rationales:

The Customer's Shared Responsibility: The customer shall express the high-level requirements, needs and expectations as much transparent as possible while providing affordable financial resources. The uncertain definition of needs and the derivation of requirements often implies misunderstanding and can lead to legal disputes. In the worst-case scenario, these weaknesses could bring to the suspension of the project and this would have drawbacks on the quality of the mission and would drive the utility perceived by the customer or user. Hence, the customer shall support the development throughout the lifecycle.

The Responsibility of the Contractor: Contractor must carefully project and review his tasks via socially accepted guidelines and legally confirm the cost and schedule for project implementation. Internal resources shall be assured, and quality standards shall be applied for the project accomplishment. Misunderstandings of what is needed to the project development may lead to extensive technical divergences among involved entities and, consequently, to weak project performances.

The Integrity of all Subprocesses: The different processes, which constitute the entire project, have to be accomplished individually in order to fulfil the overall project goal. Intermediate tasks must be reviewed and approved via reviews and milestones. Misunderstandings may lead to work overloads and to resource and cost issues.

The Value-Adding Process: The project must guarantee that the mission will observe the requirements which shall be acceptable by the customer. This aspect aims to avoid overdesign caused by the designer's own ideas, which may imply overrun of costs and schedule as well.

The Satisfaction of the Customer: Customer satisfaction is fulfilled via project control, i.e. tasks performed according to derived planning and requirements, and when customer's needs and goals are accomplished. Poorly performing missions can often be linked to inefficient understanding of customer needs.

Therefore, only fully understating and balancing stakeholders needs, project planning, project execution, and requirements derivation will lead to a so called "win–win" scenario for all project partners.

According to the described process and in order to standardize and to assist project lifecycle, most important processes and management tasks are regulated and controlled by dedicated quality management methodologies according to ISO 9001 [4], ISO EN 9100 [4] and the European Cooperation For Space Standardization (ECSS). These are applied during the individual phases of the life cycle of a space project. In particular, the ECSS are internationally accepted and are in accordance with NASA's Mil-Std (military standard) series. They are subdivided into three parts as shown in Figure 5: Engineering standards (E-series), Product assurance standards (Q-series), and Management standards (M-series).

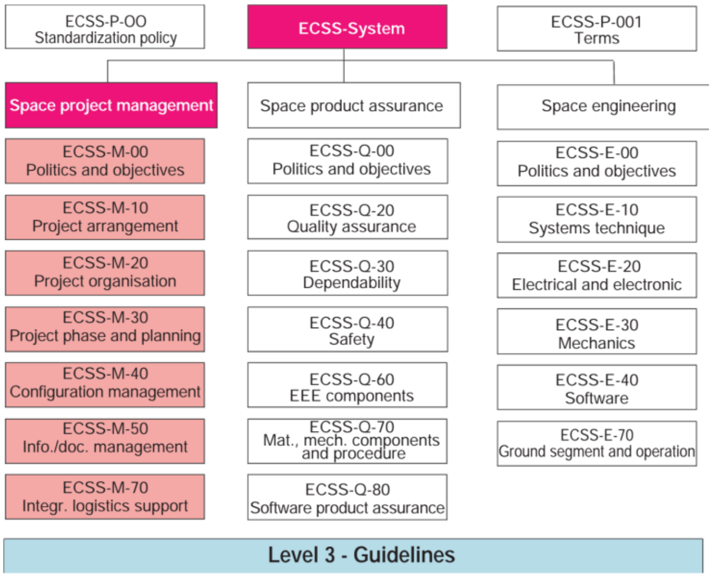

Figure 5 ECSS classification

An overview of the project phases as described in ECSS-M-30 [5] is given in Figure 6.

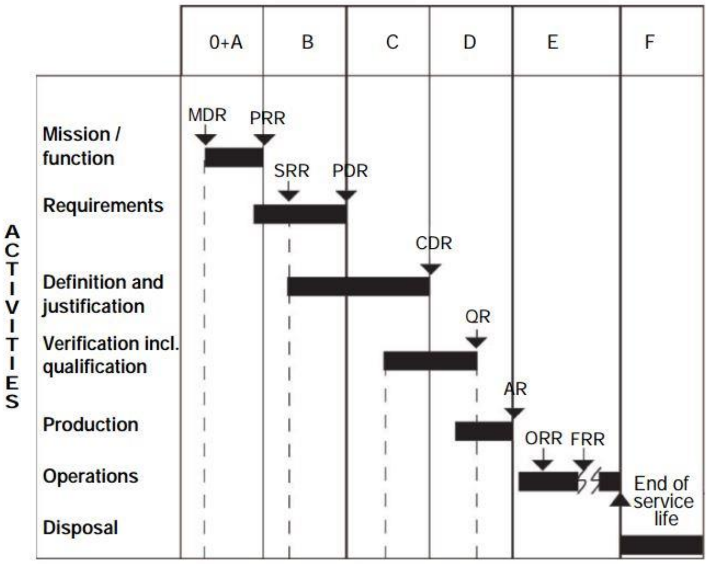

Figure 6 Space program life cycle and phases [5]

Each project phase is ended by ad-hoc reviews in which a selected review board checks out the achieved results, draws follow-up actions, and validates the passage to the next phase (see Appendix A for more details about lifecycle phases and reviews characterization).

The project schedule is applicable for all involved subcontractors, who are coordinated with the main contractor at the system level (*topdown* approach) as shown in Figure 7.

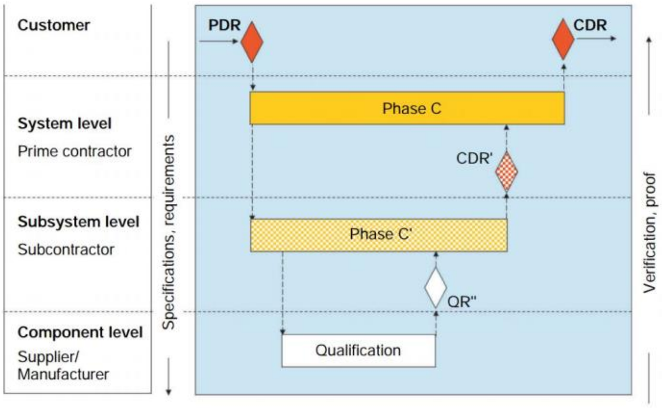

Figure 7 Stakeholder hierarchy and project phases[1]

Reviews and approvals remain under responsibility of the customer. The contractors have to ensure the required performance and services as inputs. After positive reviews, the customer allows payment, which is usually scheduled in accordance with major reviews.

The ESA approach applies to all European space programs and its institutional customers. Nonetheless, ESA approach can be tailored according to project needs, taking into account technical implementation, risk, safety and financial efficiency [6].

Pit Stop

Modern space project management approaches are aimed to assure a harmonic balance of interests in successful projects, which nowadays are always more and more stakeholder and benefit oriented.

The management of stakeholders, project schedule and requirements constitute the pillars for mission success.

1.2 Space mission design: costs and complexity

In recent years, one of the main constraint, which can also be seen as a driver, to the involvement in space-related activities has been the high cost characterizing traditional space missions. As it has been previously introduced, during the early years of space exploration, most missions were indirectly financed by governments. However, after the 1970s the *involvement of new actors in space industry began to increase*, but the high costs involved in space sector still tended to encourage governments and large commercial industries. Nowadays, in order to stimulate again the market and to involve new stakeholders, several innovative missions have been proposed and studied, trying to lower the cost to access to space. Indeed, commercial organizations are trying to exploit business plans to gain funding, and in parallel, government-funded missions are aiming towards more *cost-effective space missions*.

On the other hand, it is important to highlight that space missions are constituted by complex systems, which involve arduous cost estimation due to poorly-defined and difficult-to-evaluate subsystems, interface, and/or ambiguous and difficult-to-develop management and programmatic approaches. Going into details with the concept of complexity*, common complexity factors* involved in a typical space mission can be summarized in four areas:

- project technical design complexity;
- project programmatic complexity;
- lack of resiliency;
- new design challenge.

The latter areas picture the characteristic of complex systems, where there are a number of closely coupled, interacting, and poorly characterized design and/or programmatic features that can produce multiple, unpredictable and potentially adverse outcomes, as highlighted in [7].

The pinnacle of this complexity is reached during the early stages of concept development where performance, lifetime, environmental and interface design are not yet demonstrated. Moreover, early design phases are exacerbated by the fact that decisions made during these phases are *immutable*: once there is engagement to a concept towards a detailed design, consumer and resource limitations (mainly budget and time) usually prevent the design team from effectively switching to alternative design solutions. These decisions have immediate and delayed costs associated with them, costs that can involve a mixture of financial, risk, technological, legal, and, moral factors of interest of stakeholders. Many of these cost divergence may be properly quantified only until later stages in the life cycle as depicted in Figure 8.

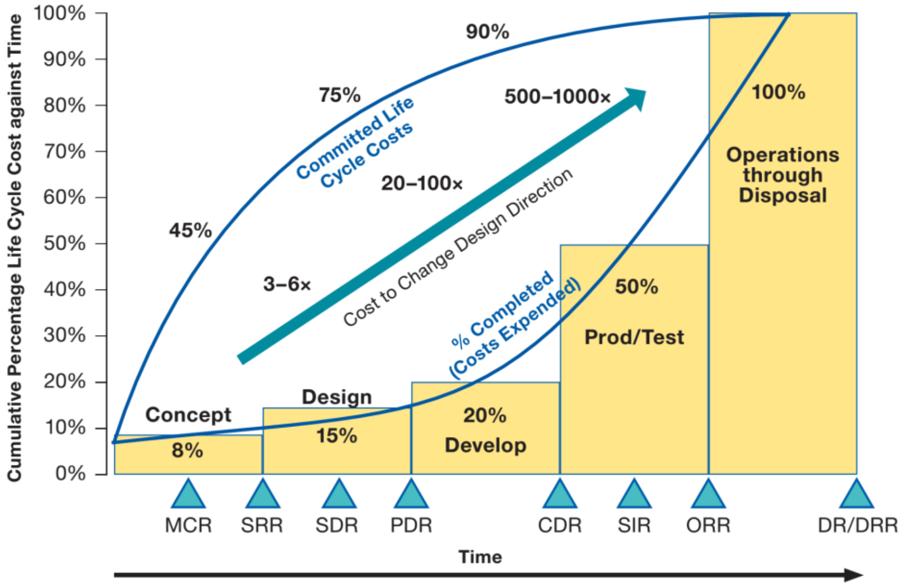

Figure 8 Cost evolution throughout the system life cycle[8]

Therefore, a poor needs analysis and ineffective conceptual design will have as outcome an even worse and expensive mission. It is valuable to observe from Figure 9 the estimated influence on the total life cycle cost with respect to only the design and production phases.

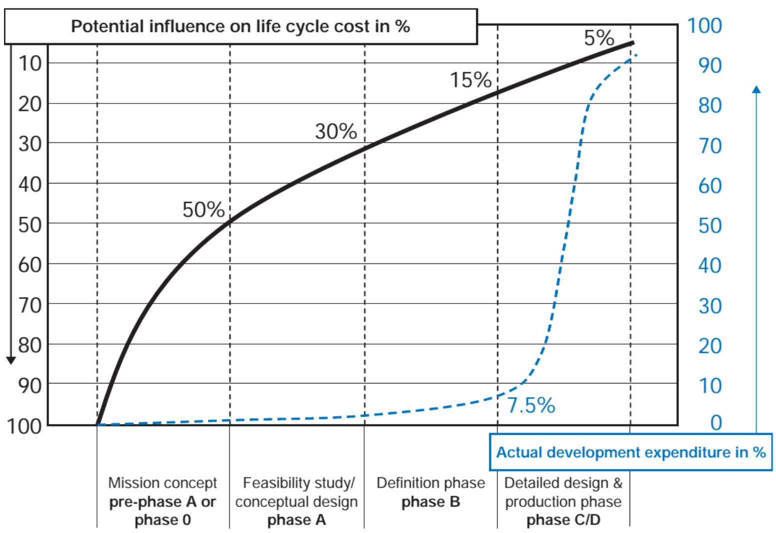

Figure 9 Potential influence of cost on life cycle cost with respect to the design phases[1]

Last but not least, Figure 10 shows how the knowledge about the system is significantly low during the early design phases (Phase 0 /Phase A). Therefore, it is necessary having a clear definition of the problem under analysis with higher value of confidence and high quality of the initial problem definition, considering the developing of alternatives.

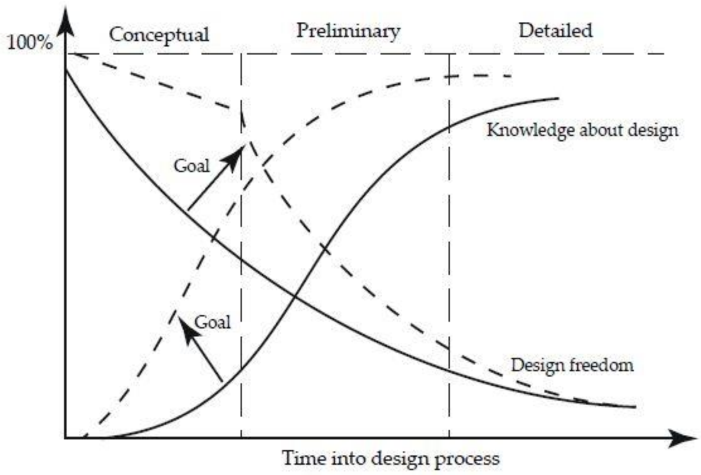

Figure 10 Knowledge of the product within design lifecycle[9]

Pit Stop

Today, numerous space missions have been created to stimulate alternative markets, mission types, and objectives by providing much lower cost access to space, thus increasing the actors involved in developing future space missions. The great majority of costs are determined by the choices taken during the early design phases, which are characterized by high complexity, low knowledge about the system and higher connection among involved stakeholders.

1.3 Space mission design: effects on mission failures

Trend in space programs shows that, since the early days of space exploration, space missions reliability have been regularly improved. Failures, when they do occur, also tend to be less significant [10]. There are, of course, some significant exceptions to this trend but, the overall driver is towards spacecraft that are more reliable and resilient. In large part, this trend is due to improvements in spacecraft components and subsystems and to the fact

that the space environment models has been characterized with greater accuracy with respect to the observed reality.
In the future, spacecraft failures are expected to continue to decline.
In order to review how symptoms of failure have changed over time, it is possible to identify categories of failures. For this intent, according to [11], failures can be classified as (1) events caused by the space environment, such as radiation damage; (2) **incidents for which some aspect of the design was inadequate**; (3) problems with the quality of the spacecraft or of equipment chosen in the design; or (4) a set of "other" failures, which include operational errors. A significant number of incidents cannot be classified due to uncertainties and are classified as "unknown."
Nowadays, designing and selection spacecraft components is built upon decades of measurement and experience in the space environment. Nonetheless, design failures remain an important cause of failure. A design failure arises when the selection and design of subsystems, equipment, either purchased or manufactured, provide insufficient performances to withstand the known a priori needs experienced during the mission. In addition, failure of a new design would fall under the category of a design failure. *Design failures are, therefore, associated with oversight or error*.

Pit Stop

A design failure occurs when a system fails even though the environment remains within expectations and each subsystem functions correctly, the failure often begins the result of *unexpected interactions between subsystems*.

1.4 Space 4.0i era: The multi stakeholder environment

The 3rd millennium brought human beings into a completely new world. Recently conceived ideas, like the Internet of Things (IoT) and big data analytics, are starting to be part of the daily life of everybody. One of the outcomes of this trend is the concept of Industry 4.0 [12]. Born in Germany [13] and afterwards spread worldwide, Industry 4.0 has modified the idea of future companies. The increasing utilization of information and communication technology allows digital engineering both products and production processes [14].

The spread of the newly born concept is gradually influencing the space industry as well, industry which historically has not been prone in advancing to great changes, due to very high-demanding safety requirements and the high level of uncertainties characterizing the space environment. With the goal of formalizing these concepts within the space industry, ESA proposes a derivation of the Space 4.0 concept, namely Space 4.0i.

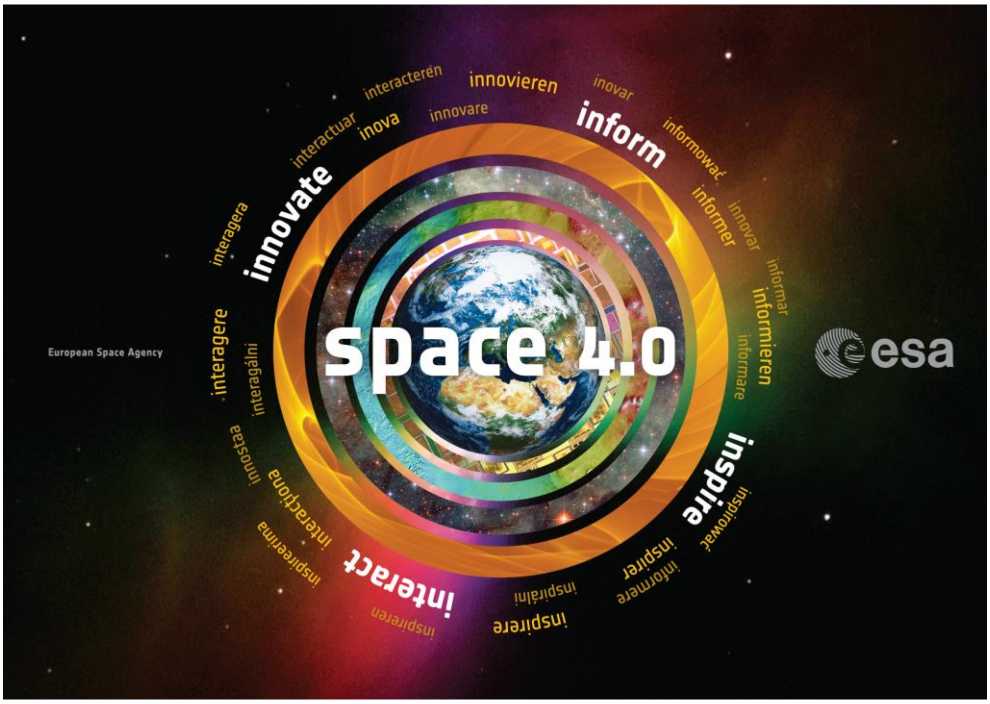

Figure 11 ESA Space 4.0i: Innovate, inform, interact and inspire (credit: ESA)

After the 2016 European Ministerial Council, it has been underlined that a new era for worldwide space industries was taking place. As introduced in the previous section, if in the past few spacefaring nations could access and influence the space field, the market is evolving in terms of number and role of the involved actors. Several aspects, e.g. the emergence of private companies, participation of academia, industry and citizens, digitalisation and global interaction, are bringing this multi-actors scenario towards an ever-closer cooperation between governments, private sector, society, and politics. After almost 50 years, s*pace is becoming competitive*, offering services to society and economy in a safe, secure, reliable, and accessible way. The basis of this vision could be found into the innovations given by excellences in science and technology, as reported in [15]. More specifically, the ESA role in Europe is aimed at implementing the Space 4.0i concept [16], where the "i" stands for:

- *Innovate*, through more disruptive and risk-taking technologies;
- *Inform*, through the reinforcement of the link with large public and user communities;
- *Inspire*, through the launch of new initiatives and programmes, for both current and future generations;
- *Interact*, through enhanced partnerships with Member States, European institutions, international players, and industrial partners.

The drawback of this collaborative concept is that new challenges are arising. The multiple stakeholders' involvement, including both national public space agencies and private enterprises, is a positive fact, giving the opportunity to shape together the next space exploration targets and to face the hurdles that may raise. *At the same time, it turns the decision-making process much more complicated*. However, sharing tasks, budget and efforts is surely way more effective than facing projects as a single entity.

Pit Stop

The multiple stakeholders' involvement, including both national public space agencies and private enterprises, is a positive fact, giving the opportunity to shape together the next space exploration targets and to face the hurdles that may raise. *At the same time, it turns the decision-making process much more complicated.*

1.5 Literature Review, Research rationale and objectives

From previous sections, it can be pointed out that history and evolution of space missions underline the undeniable truth that the design environment is not a closed word. On the contrary, it is gradually going towards an open one. It is straightforward that the design environment must be flexible and able to adapt to the external interactions, e.g. political, economic and technical environment. Moreover, it is possible to observe that the success of a space project from any supporting part depends essentially on the detailed definition of needs and resulting objectives definitions. Only then, the execution and implementation steps between the beginning and the end of a project can become visible and predictable. This detailed planning is the baseline for the control tasks of project management. This becomes critical if, as it is usual in space programs, several project parties, organizations or companies are involved and they must be guided and controlled.

However, the interests of these parties may conflict and, accordingly, influence and disturb homogeneous project execution. Some examples are: (i) the contractor need to achieve a quality product with a minimum investment; (ii) the desire of the contractor to maximize both profit and return on investment during project execution; or (iii) the desire of the project team to maintain an even distribution of workload during project execution. Most of these are certainly incomplete and imprecise. However, they illustrate what must be considered by project management for a successful project execution. While the social competence of the project manager is important for balancing the individual interests of the project partners, the manager's technical and methodological competences are essential for the successful execution of the project for the benefit of all partners.

As previously highlighted, nowadays success or failure of a program is less and less determined by its technical challenges than its management and design accomplishments. Many failed or collapsed programs may be due rather to mismanagement or design interface errors than to failure to meet technical challenges. Moreover, along the mission lifecycle, the early stages of a space project are the period where situations are often unknown, and goals are not totally defined. In these stages, there is more synthesis than analysis, the work is performed by small teams and the interactions of the Customer with the User and Sponsor are strong.

Infusion of concurrent engineering in academic environment

In order to maximise the design performances, such as number of studies, quality, costs and effectiveness, an alternative to the classical design approach has been developed based upon the consolidated benefits proven by the application of systems engineering methods. The goal was indeed to enhance the classic design approach by providing a more performant design guideline, taking full advantage of modern information technology and model-based systems engineering. This approach can be identified as 'concurrent engineering'[17]. From this prospective the first research question arises.

Q1: Would it be valuable to adapt the concurrent design approach within the academia? Would it be beneficial in terms of learning effectiveness? How can industrial approach be tailored to academic porpoise?

In this sense, Abbas et. al [18] provides a study about the discrepancy between current Industrial and Systems Engineering, university program and industry requirements in the US. During the interview sessions with industrial experts, about 90% of interviewers identified several gaps between what university, education and organizations really need. In a 2013 study based on National Association of Colleges ad Employers, 200 different employers have been surveyed about the skills they are looking for in recent college graduates [19]. The study found that the most important skill in a new hire is the ability to work in a team and, immediately at the second place, the decision making and analysis capabilities, which have strong connection with industrial and systems engineering [20]. Furthermore, an essential skill for industrial and system engineers is the ability to think in system terms, in order to assess the desired and undesired consequences of their behaviour and actions. The ability to work in a team and to enhance system-thinking approach sounds perfectly suited for the application of Concurrent Engineering within Academia in order to fulfil the needs raising from industry stakeholders. The first question can be thus summarized as:

How can we effectively adapt concurrent engineering within academia? Can the design approach be enhanced for both industry and teaching porpoise?

Evolving the current concurrent engineering approach towards Space 4.0i Era

Once put the current concurrent engineering approach and the new coming trends of space industry under analysis, it results from previous section that nowadays performances, constraints and mission effectiveness are driven by stakeholder needs and these are also biased by decisions taken during the system life cycle. Therefore, a weak needs-analysis and conceptual design will lead to an even worse and more expensive system at the end of the process [21]. Hence, in recent years, the need to exacerbate the design scenario for resilience in complex systems is increasing due to interconnected stakeholders, rapid technology advances and environmental threats. In order to engineer resilient systems, system designers and managers must take into account design options considering various scenarios, missions, functions and their performances measures, uncertainties [22].

To handle these needs for alternative exploration while speeding up the conceptual design process, promising methods have been analysed in this research. Among them, tradespace exploration can be considered as the most promising one and it can be defined as follows:

A process by which a large number of alternative designs of the same system are automatically generated and graphed against two or more objectives. [23]

In this definition, an objective is intended as a collector of a set of related attributes of a system. Attributes are measurable proprieties of the system design that are valuable for the involved stakeholders (refer to Chapter 4 for more detailed information).

Different alternatives exploration methods have been developed, from deep roots in response surface analysis methods [24], which dates back to 1950s, and optimization via design steering [25] from the 1990s, but tradespace analysis became a technique of its own in the early 2000s. Timothy Simposon and Michel Yukich from Pennsylvania State University, with the practical multidimensional tool [26], and Adam Ross from the Massachusetts Institute of Technology, with his integration of utility theory within the Multi-Attribute Tradespace Exploration (MATE) framework [27], brought tradespace exploration into stronger consideration. In particular, the purpose of MATE approach is to capture decision maker references and to use them to generate and evaluate a multitude of system architectures. On the other hand, MATE *does not create the problem of trading off among multiple decision makers*, but rather makes the trade-offs more explicit.

Modern engineering projects increase in size, complexity, and number of people affected by the mission itself. It should now be clear that, when more than one party is involved in the decision-making process, the identification of a single design solution becomes more challenging, as the preferences of different stakeholders must be balanced and satisfied contemporary, even in the case of conflicting interests. Stakeholders generally aim for their own interests but, at the same time, they have to take into account the needs of the entire group and they have to face the impossibility of retreating from the design process. The common approach to address multi-stakeholder decisions in system engineering is by aggregation of requirements from each stakeholder, as detailed in [28]. A design methodology, constituted around requirements, is often called "requirements engineering" and it involves various methods and techniques, as presented in [29]. Thus, it is appropriate to analyse challenges of requirement-based engineering design due to following characteristics:

- *Distinct objectives*: there are multiple decision makers. Each of them has his/her own objectives, which may conflict with each other. This misalignment of objectives also causes potential inefficiency for the entire engineering design.

- *Interdependent decisions*: decision of each design team may affect performance/interest of another design team.

A decision maker needs also to consider how others may response to his/her actions. Considering the presence of different people within the design environment is more and more demanding. Following the classic requirements engineering approach, the collection of requirements between stakeholders' results in a system designed by a single master stakeholder, characterized by a set of different and complex needs.

Lately, the challenges in implementing requirement-based engineering design have received a lot of attention. Firesmith [30] summarized some practical problems of using requirement-based engineering design, among which: (i) poor or ambiguous requirements; (ii) incomplete, inconsistent, incorrect and out-of-date requirements; and (iii) changing requirements over time. For each of these problems, the author suggested some industry best practices, indicating that poor communication and cooperation between different design teams is one of the major causes. The field of collaborative engineering is referred to this high-degree of interaction between stakeholders as either collaborative or cooperative. Indeed, as corroborated by [31],[32], collaborative negotiation has received significant attention in recent years. Past literature also shows that performance of requirement-based engineering design can be improved by increasing the quality of requirements and allocating them in an efficient way, as suggested by [33]–[35]. In particular, there are two common approaches to allocate resources, e.g. allowable weight, size, power, length, in requirement-based engineering design: (i) third-party driven approach; and (ii) individual-driven approach. In third-party driven approach, resource allocation is carried out by a third-party committee, whereas in an individual-driven approach the resource allocation is carried out by a project member. However, both approaches share some common shortcomings, leading to a more suboptimal design solution. For example, the direct allocation of functions to specific architecture elements could pilot to a set of solutions but could inhibit an effective exploration of the trade space. Other limitations of requirements engineering that have challenged system engineers can be found in Fitzgerald et al. [36], including:

- Requirements may constrain solutions on specific areas of the solution space too early in the design process;

- Hierarchies in set of requirements can cause downstream disruption in the design process when they must be changed. Specifically, for aggregating multiple stakeholders' requirements:
    - Unequal number of requirements for different stakeholders indirectly (and usually unintentionally) weights the resources allocated to them in detailed design, with possible negative consequences;
    - Aggregation limits the opportunity to examine trade-offs between different needs, as they become amalgamated.

In literature, utility theory is usually considered as a valuable alternative to requirements engineering, due to its ability of overcoming many of the introduced challenges. Many utility-oriented researchers have come towards the multi-stakeholder problem with the goal of aggregate utility and maximization of social welfare between stakeholders (see [37], [38], and [39]). Efficient methods to achieve this goal can be found using algorithms to generate "optimal" or Pareto-efficient solutions, and applying the principles of game theory in order to model and simulate negotiation, as presented in [40], [41], and [42]. Game theory is originally developed in mathematics and economics and, nowadays, it is widely applied in marketing [22], [23], supply chain [21], [24], and operation management [28] to characterize competitive behaviour in market places. Indeed, it offers an effective tool to characterize interactions between decision makers.

In an ideal and rational world, the decision makers would have complete information of the preferences of each stakeholder. However, this information set is incomplete and/or fuzzy. Furthermore, aggregation of the utility functions of different stakeholders suffer because there is no global scale of utility that can be compared across individuals. Hence, the results of such techniques should be handled with caution and the solution should be seen less as "optimal" designs and more as "interesting" ones.

When dealing with optimality and with the research of the design objectives "maximization", such as in the case of the tradespace exploration, a guided search for the pareto front by optimization algorithms would be beneficial. Moreover, optimization is becoming a promising approach into the space system design as well, in both research and industry environments. In space system design practise, there are many areas where optimisation can be applied with advantageous results, as reported in [43]. Some examples are given by:

- Mission analysis and trajectory planning;
- Planning and scheduling;
- Payload accommodation;
- System design;
- Payload performance;
- Observation data handling and remote monitoring;
- Cost and revenue management.

Concerning the multidisciplinary nature of space systems, the domain experts, stakeholders and the design constraints involved in the product lifecycle, a promising method for handling this kind of problems is given by the Multi-Disciplinary Optimization (MDO). Besides the multidisciplinary nature of MDO approach, practical implementation highlights several benefits with respect to the final outcomes:

- The time required in the design cycle can be significantly reduced;
- Sequential optimization of disciplines may lead to a suboptimal solution for the whole system (bottom-up vision);
- Disciplines and stakeholders with conflicting objectives can be resolved.

From this emerging trend of increasing the effectiveness of exploration of design alternatives via advanced tradespace exploration and concerning a design aimed at multi-stakeholder value delivery, a second set of research questions arise straightforward, as follows:

Q2: Can we improve, using quantitative methods, the level of quality and quantity of information aiming to obtain a "better faster and cheaper" space missions and systems design?

To answer this question and the derived ones and to provide the state-of-the-art and current trends of systems engineering and design methods, this research presents an innovative concurrent design methodology, which aims to exploit modern systems engineering methods and tools, speeding up the space mission early design processes, increasing the amount of information, and assisting the decision making processes while guaranteeing the technical feasibility and stakeholder satisfaction. This goal can be achieved by an ad-hoc assistance to design experts and, more in general, stakeholders with a generation and exploration of a "*negotiation space*", providing a metric to evaluate several system design options from a negotiation point of view, taking into account the resilience and robustness of the design itself. This methodology aims at providing benefits that will entail great improvements in handling negotiation problems in system design, reducing the iterations needed to reach at the convergence of the design while keeping all the stakeholders satisfied and reducing space program cost and complexity.

This proposed design methodology is also aimed to evolve and challenge the state-of-the-art given by the requirements engineering approach, by postponing generation of requirements later in the early design phase, only a-posteriori, to a stable and social accepted negotiation process. Last, it emerged from the literature review that the guided exploration of design alternatives and the understating of negotiation processes would also be beneficial, transversally from industry to academia applications.

Pit Stop: Summary of Research Questions

This research set out to answer the following questions which were selected as driven for the future development of space mission, improving early design effectiveness:

Q1: Would it be valuable to adapt the concurrent design approach within the academia? Would it be beneficial in terms of learning effectiveness? How can industrial approach be tailored to academic porpoise?

Q2: Can we improve, using quantitative methods, the level of quality and quantity of information aiming to obtain a “better faster and cheaper” space missions and systems design?

Q2.1: How can we assist team of interconnected stakeholder in early decision-making phases? Is it possible to model and optimize the negotiation processes in a reliable way?

Q2.2: Given the state of the art and the trend of systems engineering methods, how can we infuse negotiation processes within the tradespace exploration phases? It possible to have a user-friendly alternative exploration focused on social welfare?

Q2.3: How can we automate recursive processes, exploiting team knowledge, increasing the reliability of the solution design?

1.6 Research methodology

The research gathered information from real programs through three main methods: (i) hands-on activities; (ii) literature review; and (iii) active development. The participation and organization of different activities related to the concurrent engineering approach allowed to gather information and to identify areas in which focus the research activities.

Figure 12 Research Methodology in a nutshell.

These activities were carried out in order to understand the current gaps or possible enhancement within the design approach while evaluating its possible extension to a university environment. In particular, the Aeronautics and Space Agency of FFG /ESA Alpbach Summer School and the Concurrent engineering Workshops and Challenges organized by ESA academy offered an important pillar, from which it has been possible to begin the topics selection.

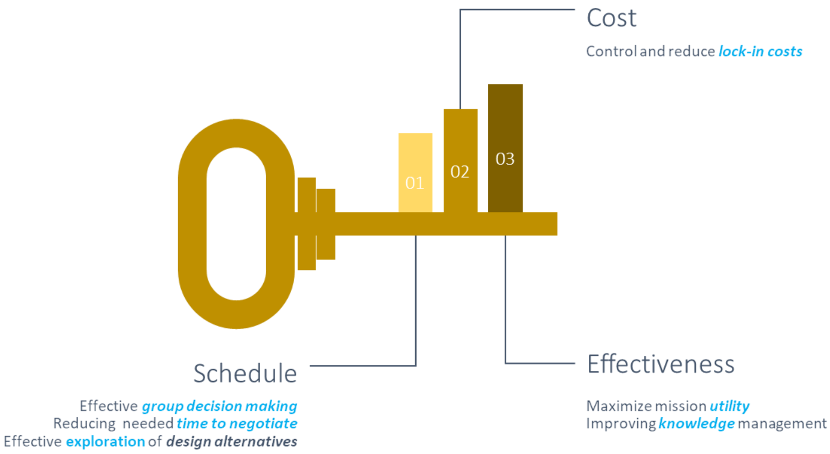

Figure 13 Research Keywords

Once the research areas have been identified, a literature review and a follow-up development have been carried out. Finally, the developed enhancement has been validated via algorithm-in-the-loop simulations and ad-hoc hands-on activities. The research has been carried out keeping in mind the three keywords displaced in Figure 13. The following sections will analyse in detail the research tools and methodologies applied throughout the research activities.

1.6.1 Literature Overview

This research is aimed to a synthesis of modern systems engineering methodologies, with particular attention to the concurrent engineering approach. Following the Space 4.0 philosophy and keeping in mind the aforementioned issues arising during early design phase, important insights were given to "non-engineering" fields such as psychology, group dynamics, behavioural economics, multidisciplinary optimization techniques, and artificial intelligence. The literature review was initially carried out targeting on one side the concurrent engineering approach, identifying the state-of-the-art and possible improvements, and on the other the trade space exploration techniques. This review aimed to have a better understanding of the current design approaches, identifying possible enhancements and structuring the body of the research. Afterwards, in order to address the research questions, great attention has been given to other topics (e.g. multi attribute utility theory and game theory), mainly from "non-engineering" fields of research, with the goal of getting insights about promising methods to be effectively applied in the systems engineering domain, especially if the methods were well-suited to address the challenges within negotiation and resolution in the engineering design.

1.6.2 Theory Building

The process of theory building followed the structured process shown in Figure 14 and suggested by Carlile et al. [44]. Within this research, the first step of phenomena observation has been carried out via literature overview and hands-on experience, focusing on people, organization, technologies and processes to handle both concurrent engineering and multi-stakeholder tradespace exploration. The categorization phase was focused on the identification of category of groups and team decision-making approaches, categorizing also the circumstances in which a particular attitude can arise within a team. This aimed not only to properly build a solid theory behind the multi-stakeholder negotiation process, but also to understand the team dynamics and team-building approach within a Concurrent Engineering Team (see chapter 2 for more details). For the relationship phase, the work tries to correlate and model the attitude and group dynamics in order to answer the derived research questions.

Throughout the research activities, as displaced in Figure 14, the theory building process represented an iterative loop, from inductive to deductive phases, confirming and predicting assumptions and the actual effectiveness of the proposed methodology, aiming to a final convergence of the preliminary answers to the research questions.

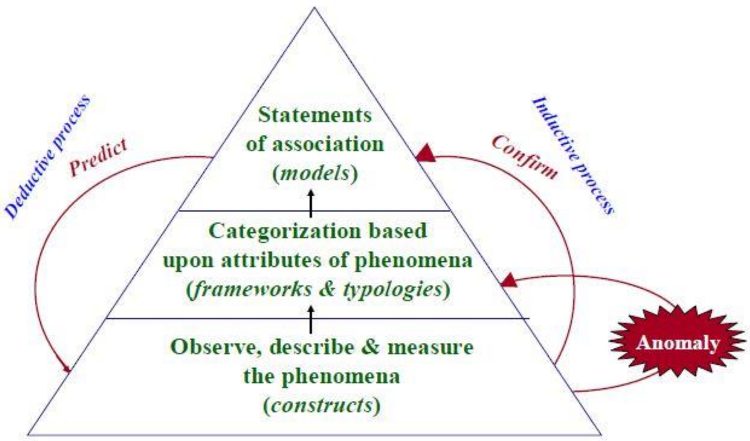

Figure 14 The normative theory building pyramid [44].

1.6.3 Interface with practise

Besides the theoretical contribution provided by this research, one of the objectives of the work described in this Thesis targeted the research questions by the practical application of concurrent engineering and tradespace exploration (TSE) has been carried out, with the intent of:

- Understanding the application and the challenges of modern systems engineering and the concurrent engineering approach;
- Exploring the possible application and challenges within the concurrent engineering in an academic environment;
- Understanding how to extend the application of multi-stakeholders problems within end-to-end design process;
- Ensuring the applicability, feasibility and effectiveness of each observation that have been derived during this research activities.

Figure 15 Interface with practise: Alpbach summer school and ESA academy concurrent engineering workshop 2016 (credit: ESA).

This phase not only assisted with the beginning and with the following iterations on the theory building processes, but also it assisted with the derivation of a robust methodology to reduce the barriers with a “real word” application of MONET, both within academia and industries.

1.6.4 Application to case studies

The developed methodologies were applied to several case studies in the domain of space mission conceptual design. In particular, a CubeSat mission for lunar exploration within an ESA initiative and a Small Satellite mission for Lunar south pole observation within an ESA academy concurrent engineering challenge have been selected. The application to case studies, as pictured within the structure of this manuscript, serves to clarify and assist the application of the developed methodology to possible users/adopters. The case study was also able to provide more information and data to iterate in the theory building process. Case studies are indeed necessary to support validation process, which is often challenging for human-in-the-loop methods and processes. With the goal of having a more reliable results, the insights obtained by the application of MONET were compared against the state-of-the-art methodologies.

1.7 Thesis organization

The thesis has an organization, which tries to give a structured path for the reader. One of the crucial objectives of this work is to provide an overview not only on the new developed methodology proposed in this Thesis but also on methods and processes within the concurrent space mission design and on decision making approaches. Thus, the remainder of this Thesis is organized as pictured in Figure 16, providing a snapshot of the research activities with relevant chapter highlighted, and detailed as follows.

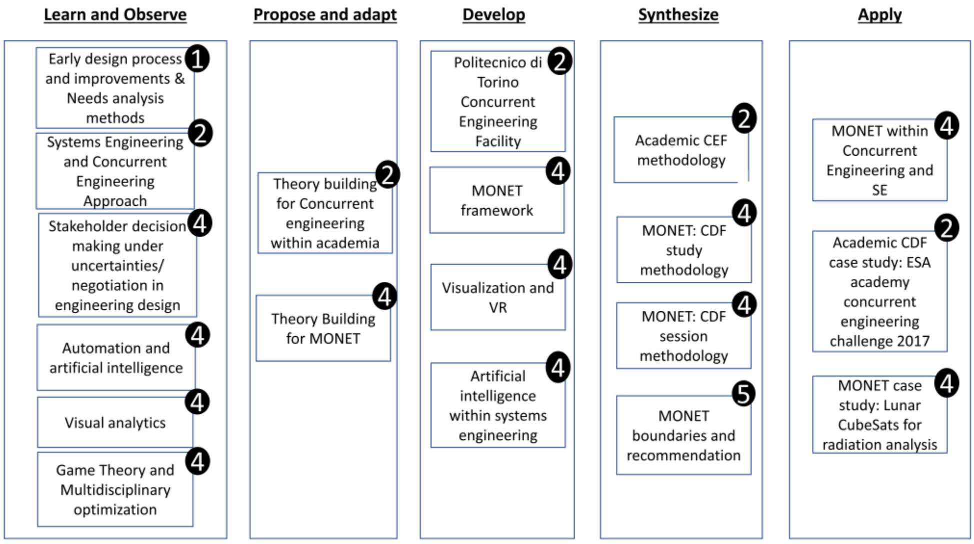

Figure 16 Thesis organization.

- *Chapter 1* Introduction and rationale (this chapter) contains a brief introduction to the research, giving some inputs about its goal and rationales.
- *Chapter 2* Review of systems engineering and design approaches: This Section describes state-of-the-art for design approaches and engineering facilities, establishing a basis upon which the current research is built.
- *Chapter 3* Ladybird guide to academic concurrent engineering: This Chapter gives a complete summary of the concurrent design approach and concurrent engineering facility, with a focus on the application of the design approach within academia. Design methodology, team building, team management, software and support infrastructure are presented. The finalization of the design methodology and the final findings are offered based on application of the developed concurrent engineering facility to case studies and to the first ESA Academy concurrent engineering challenge 2017. This chapter addresses the research question Q1.
- *Chapter 4* Multi-stakeholder negotiation space exploration: This Section describes in detail the developed design methodology, which exploits the knowledge gained form the state-of-the-art analysis. Attention will be given to stakeholders needs analysis, negotiation approaches among different stakeholders and fast exploration of design alternatives, all applied in order to the support to actual concurrent engineering sessions. Each subsection of this Chapter is structured by following the developed process. For each process, an introduction to the theoretical building blocks is given

in order to give to the reader a basic comprehension of the described process. Findings are offered based on application of the developed methodology to a selected case study. This chapter goes through the research question Q2 and the derived ones.

- *Chapter 5* Conclusion and recommendations: Discussion of results provides a logical analysis of the results, possible indications of causality, and their limitations, including examples of how the results can be used during or in advance of a system development program.

Appendices and glossary provide supporting information including, bibliography.

Chapter 2

Systems Engineering and Concurrent Engineering

"If we want to solve problems effectively...we must keep in mind not only many features but also the influences among them"

Dietrich Dorner in: The Logic of Failure: Recognizing and Avoiding Error in Complex Situations

The analysis of research context and the observations of current trends in modern project development, highlighted that structured project organization, team collaboration and stakeholder value delivery are fundamental drivers to achieve project success. A methodology to ensure the goodness of a product lifecycle, according to the latter drivers, is given by Systems Engineering (SE).

The term systems engineering dates back to Bell Telephone Laboratories in the 1940s, but the introduction of the concepts of systems engineering goes back to the Bell Labs since early 1900s [45]. In industry, the term ‘‘systems approach’’ has been adopted for the first time during the research and development of the black and white television [46].

The development process in systems engineering is commonly viewed as a decomposition (or design) process followed by a re-composition (or integration) process[47]. During the decomposition process, stakeholders’ needs are analysed and translated in engineering terms and then partitioned into a set of specifications for next allocation to segments, elements, or components. This design process must be extensive in perspective so that nothing is left out and every contingency is considered. Systems engineers must be ‘‘*big picture*’’ technicians to be able to bring a unique value to project development.

2.1 Systems engineering in program development

In order to understand the real value of systems engineers within a project development, a quantitative research project was developed by Eric Honour and the University of South Australia with the goal of quantify the Return Of Investment (ROI) of Systems Engineering (SE) activities. In this research, Honour explores the quantitative relationships between systems engineering and program success. The program, created around an interview process, is based on a peer-reviewed ontology.
Its first six findings are of highest importance to the SE discipline and to the system development programs that exploit SE, in particular according to Honour et. al. [48]:

1. There is a positive quantifiable relationship between systems engineering effort and program success.
2. Systems engineering has an important and quantifiable Return of Investment.

The quantified interrelationship between cost and total SE effort was evaluated as function of standard financial calculations for Return on Investment. The return was evaluated as program cost savings and the investment was measured as additional cost applied to total SE effort.

3. No correlation was found between systems engineering and system technical quality.

The third measure was intended to quantify the technical quality of the final system, using identified Key Performance Parameters (KPP) of great importance for primary stakeholders. Major finding consists in putting caution for the SE tasks, it is important to avoid that SE becomes an adjunct of program management. The role of SE in a project is to monitor and guiding the project technical success. Today, it appears that technical requirements are measure of technical success, rather than the technical qualities that matter to the stakeholders. This point underlines the fact that a system with fulfilled technical requirements is attractive to program managers and contractors but does not produces the best systems to the primary stakeholders.

4. There is an optimum amount of systems engineering tasks for best program success.

The quantifiable correlations between SE effort and program success can also evidence a "bathtub" evolution in which there is a clear optimum value of SE effort. This optimum has been evaluated by the determination of the point at which the ROI goes to zero, in specific, the optimum amount of effort for a program is 14.4% of the total program cost[48].

5. Programs typically use less systems engineering effort than is optimum for best success.

For the median of the interviewed programs, the calculated ROI is 3.5:1. This indicates that additional SE effort would result in a program cost reduction 3.5 times as great as the cost of the additional effort.

6. For systems engineering effort estimation, some program characterization parameters are of much greater importance than others.

This finding shows that it is necessary to take into account all of the important program aspects when estimating program SE effort, a similarity analysis and criticality one might serve as good tools for this estimation.

7. Of the SE activities, technical leadership/management is unique in providing optimum program success simultaneously in cost, schedule, and stakeholder acceptance.

SE effort has a compelling and quantifiable influence on program success, with correlation factors of about 80%. Increasing the percentage of SE effort within the project development and implementation results in an outcome up to an optimum level.

Pit Stop

Most programs operate with less Systems Engineering effort than is optimum for program success. For most programs, increasing Systems Engineering effort can be expected to significantly reduce the total development cost and time, increasing final system effectiveness.
The role of Systems Engineers in a project is to monitor and guiding the project technical success towards the technical qualities that matter the most to stakeholders.

2.2 Design approaches

Along with systems engineering effort and the structured program management approach illustrated in the previous sections, it is important to analyse design approaches and design methodologies applied by companies and/or agencies in their design phases.

The word *design* is used by many professions (artists, architects, all disciplines of engineering), the American Heritage Dictionary defines design as: "de-*sign (di-zin') v. -signed, -signing, -signs. –tr. 1. To conceive in the mind; invent: designed his dream vacation. 2. To form a plan for: designed a marketing strategy for the new product. 3. To have a goal or purpose; intend. 4. To plan by making a preliminary sketch, outline, or drawing. 5. To create or execute in an artistic or highly skilled manner. –intr. 1. To make or execute plans. 2. To create designs. –n. 1. A drawing or sketch. 2. The invention and disposition of the forms, parts, or details of something according to a plan. 3. A decorative or artistic work. 4. A visual composition; pattern. 5. The art of creating designs. 6. A plan; project. 7. A reasoned purpose; intention. 8. Often designs. A sinister or hostile scheme: He has designs on my job".*

It is possible to summarize the engineering design of a system as all the preliminary activities whose purpose is to satisfy the needs of the stakeholders. The scratch idea begins in the mind of the engineers but must of them need be transformed first in models, exploiting computer aided design techniques, towards final physical models. It is necessary to underline that while this research goes through engineering methods, processes and tools used during design process, there will always be an element of creativity that is required for the design process and for a successful achievement of the system goals.

They might be several ways to approach the design problem. A design approach is a general philosophy that guides the behave and information exchange standards among the engineering team. A combination of approaches may be used if they don't conflict. Throughout engineering practice, it is possible to identify three major types of design approaches namely: (i) sequential design, (ii) centralized design and (iii) concurrent design.

Sequential design approach

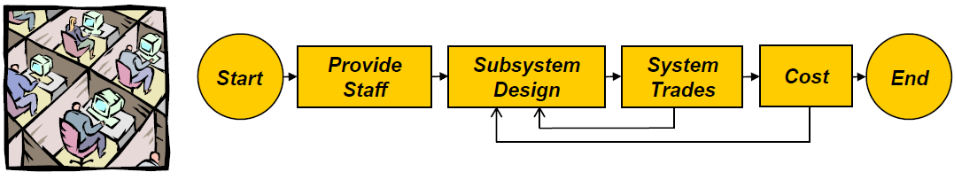

Figure 17 Sequential Design

The sequential approach, schematically represented in Figure 17 , constitute the most 'classical' design approach. In this approach, the design passes sequentially from a domain expert (working separately from the design team) to another. It can be approximated as a sequence of specialists working 'in series. The analysis and correction of design inconsistencies, done in order to guarantee the design convergence, is gained thanks to the process iterations. Because of communication lacking among team members, wrong assumptions may be employed during the design process, system design parameters are not monitored in real-time, thus several iterations may be necessary to reach design convergence. The sequential approach has nonetheless some advantages, such as: flexibility in manhour and manpower resources utilization and the fact that it is a consolidated and well validated process. On the contrary, as part of the disadvantages, it reduces the chance to explore interdisciplinary solutions and to infuse awareness of the system in the experts. Moreover, since all the design data and models are dispersed among the experts it is very struggling to re-assemble all this knowledge. Finally, the sequential approach suffers from the time-consuming approach characteristic. The time required for performing studies using the classical approach (6–9 months) was indeed incompatible with the evolution towards a shorter time-scale from concept to final system delivery.

Centralized design approach

An improvement to the sequential approach is represented by the centralized design approach, where the various technical domain specialists provide subsystem design information and data to a core team of one or more system engineers.

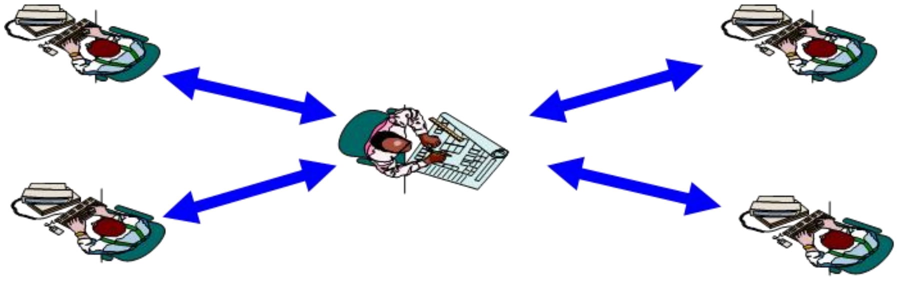

Figure 18 Centralized design approach (credits: ESA)

Their task it is to analyze and check the design at system level, promoting and encouraging communication between specialists when appropriate or required. It is straightforward that this design approach can soon bring to the saturation of the systems engineering team due to excessive information exchange, complex system management and complex team management.

2.3 The concurrent design approach and Model Based Systems Engineering

The Concurrent Engineering (CE) consists in a set of methods from which the design, development, procurement and manufacturing of a product is carried out by a quasi near-real-time teamwork [49]. The simplest definition of Concurrent Engineering (CE) is the simultaneous development of product and process[50]. This approach requires a high level of integration of tools among all the technical domains and stakeholders involved in the process, typically it is enabled by modern Information Technology. The aim of this approach is to reduce the time to mission design, cost of development meanwhile increases the quality of the developed system(s). By today a lot of effort has been spent to improve concurrent design tools and team management techniques within various applications over more than 30 years of industrial applications [51].
Depending on the design context and the development environment, various definitions of concurrent engineering have been introduced and used in literature[51].In aerospace mission development, the first application of concurrent engineering approach, with a particular focus on the conceptual design phase, can be attributable to NASA Jet Propulsion Laboratory Team X [52][53].
Thanks to the notable effectiveness of the design approach, ESA adopted and explored the approach as well, their derived definition of the CE design approach can be identified by Bandecchi et. al. [54] as:

"Concurrent Engineering is a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of cooperation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle."

There are three primary reasons that caused the design process to evolve into a concurrent process as introduced by [50]:
1) *Rapid Pace of Technology*: Technology was advancing at an increasing rate. Some companies were able to take advantage of new technologies and convert them into products, gaining more market power. This puts competitive pressure inside the companies that remained behind. Design groups were forced to develop products in shorter time, providing competitive advantage to regain the lost market position. Time-to-market, which is a term used to identify the time between the initial idea to the time the first customer product is shipped, became the competitive strategy and main driver for many companies.
2) *Forced Design Cycle Compression*: As engineers became pressured to develop products more rapidly, manufacturing needs became low or non-existent on the priority list. Engineers became focused only on deriving requirements and specifications. Product inputs from other functions that might cause a slip in the design schedule were often ignored. Thus, as SE learned more about the customers' needs and expectations, and manufacturing engineers learned more about the cost to produce the product and manufacturability issues, few of their recommendations could be incorporated into the design under development. Any accepted recommendations were incorporated only if they did not have an impact on the overall product development schedule.
3) *Emerging Information Technology and Methodologies*: New technologies were developed to help the design process. The emergence more performing computer enabled computer-aided design (CAD) and computer-aided engineering (CAE) to become more cost effective and employed in engineering tasks. Computer-aided engineering (CAE) tools, were being developed to help in the study of systems in a more technically robust and detailed approach.
In the same time, a new system engineering methodology, namely Model Based Systems Engineering (MBSE), based on electronic communications and modelling emerged to speed up the SE process. MBSE is aimed to move the design process from document centric to model centric, replacing documents with models.

Model-based systems engineering is the formalized application of modelling to support system requirements, design, analysis, verification and validation, beginning in the conceptual design phase and continuing throughout development and later life cycle phases. [55]

MBSE methodologies have the goal of improving communications, quality, increasing productivity and reducing risks within the system lifecycle. Even if the benefits provided by models are consolidated, some major improvements still need to be carried out. It might be hard to model non-functional requirements; models can be a barrier to understanding for some stakeholders and effective MBSE requires a disciplined and well-trained project tam working in a mature process approach. Nonetheless, advanced applications of MBSE in concurrent engineering is of great interest from 1991 since nowadays [56], [57].

In parallel to advanced SE methodologies and tools, the fundamental part of every Concurrent Engineering Sessions concerns the complete design team, which is composed of pre-selected technical domain specialists with the active participation of principal stakeholders. The team starts working on the different aspects of the project from the beginning of the design process. Not all the domain experts are involved in each design session, besides, the participant are chosen given the mission context and mission critical aspects.

From a process point of view, project convergence is obtained by working in quasi real-time in a common design environment constituted by constant, direct communication and design data interchange between members. The process considers iterations where all disciplines experts have the duty to share their ideas and results. This aims to minimize the risk of inharmonic developments.

In the concurrent approach every design issue, starting with the revision of mission requirements, is discussed with all the team members. Hence, there is a general awareness of the decisions taken. Therefore, all the design team members can follow the same design advancement, avoiding the occurrence of misunderstandings among the various subsystems' design, and therefore reducing the time and effort required by the mission study.

For a typical pre-Phase A and phase, A study the concurrent design approach several benefits might be found, some examples are[34]:

- The study duration has reduced from 6–9 months to 3–6 weeks
- The corresponding cost has reduced by a factor of two
- The number of studies that are performed per year has increased
- The use of CD has resulted in an improvement in the quality of these technical assessments.

The more detailed and faster assessment of new potential missions allows critical issues to be discovered and highlighted well in advance in the project life-cycle, and consequently reducing the risk of later engineering changes.

PitStop

In CE the design team members can constantly follow the same design information, avoiding the occurrence of incompatible designs of the various subsystems, and hence reducing the time and effort required by the mission study. *One of the advantages of working in the concurrent environment is that the specialists get used to keeping the 'system perspective' in mind.*

2.4 Review of practical Concurrent Engineering approach: ESA Concurrent Design Facility

The first step towards a more permanent application of CE activities in ESA required the reorganization of existing tools and human resources in a more effective way. The first solution lead to the creation of an *Integrated Design Environment* (IDE) based on Microsoft Excel®. This consists of one component that is linked domain specific tools and databases (DB) developed and shared by the various technical domains thanks to the implementation of real-time solutions for data sharing.

Besides the developed tool, it is necessary to *gather* the necessary CE expertise within the technical domain specialists and proceed with their training to work together as a collaborative *team*.

Domain experts are not permanently and exclusively assigned to CDF activities, as this is just one of the several tasks, they perform in the ESA organization.

2.4.1 The process

The conceptual model of the ESA CDF design process is shown in Figure 19, and it is conforming to the nature of complex systems design. Indeed, it is highlighted the fact that a space system has many interfaces and dependences between technical disciplines. This entails that the iterations of a parameters value have an implication on the other disciplines, and that any change will propagate through the system design.

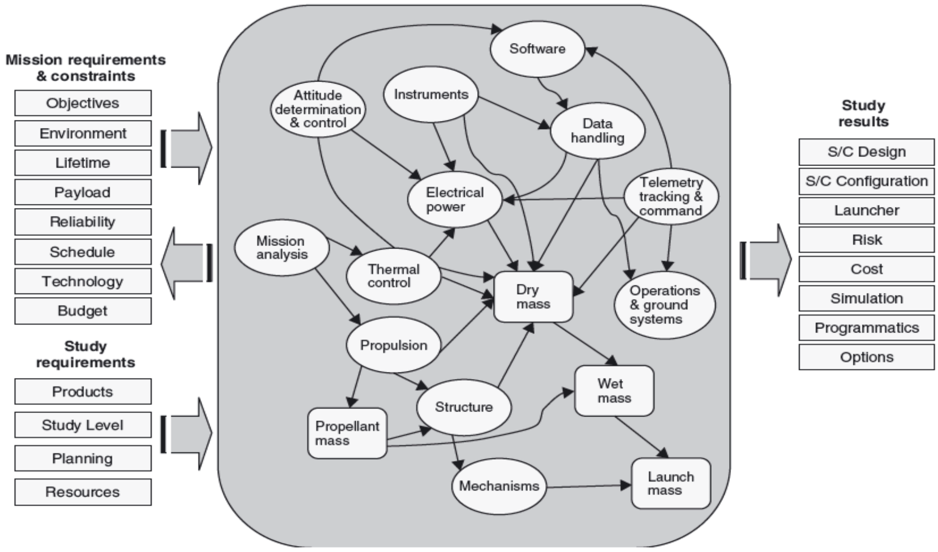

Figure 19 CDF Process [54]

Reducing the impact of parameters changes is essential to ensure that the design process converges to an effective solution.

The design process starts with a preparation/study phase in which some members of the engineering team (typically team leader, system engineer, critical discipline specialists) meet with customer(s) in order to properly derive high level mission requirements, defining mission constraints, identifying design drivers, and evaluating critical disciplines whose need to be carefully managed in order to achieve the study objectives.

As consuetude, design process begins with the study 'kick-off'. CDF tasks are conducted in a number of plenary meetings, named as 'sessions', in which experts from all engineering domains take part, vertically from the early phases to the end of the preliminary design activities.

The customer is invited to engage in all sessions along with other specialists, this will ensure immediate feedbacks enhancing the effectiveness and maturity of the design.

In the first design session the customer with the team leader share to the design team the mission requirements and constraints. In the follow up sessions, each domain expert presents the developed design alternatives related to his/her domain of expertise, highlighting drivers and interfaces with the other domains. Throughout design iterations a shared database for design parameters is exploited. Mission requirements and constraints evolve according to customer agreement and engineering process feasibility outcomes.

Ability to manage a design process that is not dependent on the path followed by the team is a mandatory attribute that needs to be implemented in every CE study. It is demanding to take advantages from design alternatives, state of the art and reduced estimation techniques to ensure that the design process is not stopped by lack of data or by missing decisions. In summary, the concurrent design process follows the *Spiral Model* shown in Figure 20.

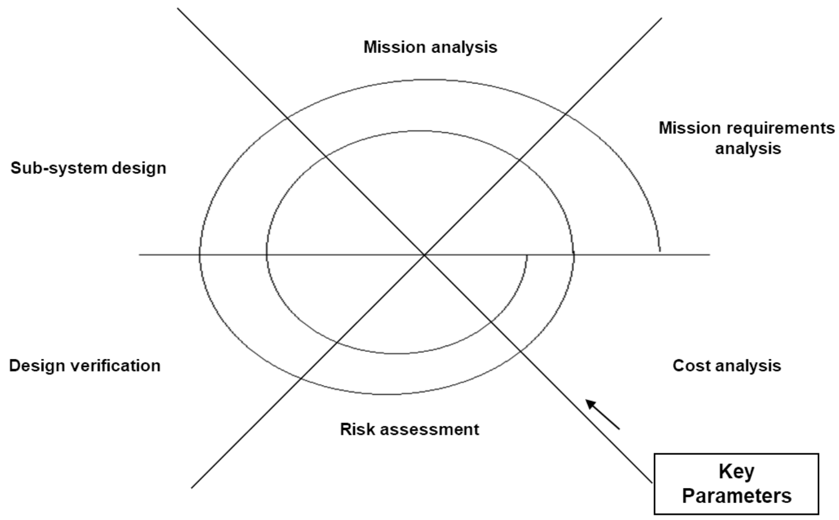

Figure 20 Spiral Model (Credits: ESA et al. [49])

A spiral path is followed throughout the design process. The space of all engineering solutions including the spiral path, is subdivided into areas, each one targeted to a technical discipline. Each discipline is therefore responsible for the evaluation of all the domain related design parameters, which are infused in that portion of the design space by the representation in the X-Y axis. Each design iteration is pictured by a turn-around, where all the disciplines present the outcomes related to the subsystem they studied.

The whole design process is built by follow-up iterations across progressively mature solutions, until all key parameters have reached the required value derived by mission requirements and constraints.

A balanced number of spirals can be foreseen and executed, in function of the previsioned number of design alternatives that the team needs to analyze within the decision-making processes. The design alternative (i.e. a spiral path) that involves the faster and more effective design convergence is usually selected as the baseline design that is promoted for follow up iterations.

Once an iteration is finished, which typically lasts *four hours*, it is a duty of the complete design team to accept all of discipline's proposal and collaborate to final decisions on the design trades. The agreement on a design solution lead to publishing the current design data in the central repository, making them available to the other domain experts for their evaluations.

This process is than repeated until the impact of the change has been propagated to the point where design iterations no longer have a significant effect, which, roughly speaking can be seen as verifying the whole set of mission requirements and mission constraints.

2.4.2 The team

Discipline experts working in quasi-parallel manner in the same room are not enough in order to create an effective collaborative environment.

Without a proper team composition, it may become a place where conflicts are triggered. Hence, it is mandatory that the group of specialists must perform as a team.

The motivation of the team members should be encouraged by fostering the novelty of the method, the collective approach, the co-operative environment, the intense and focused effort and a clear, *short term goal*[49].

In addition, the configuration of the team and the choice of disciplines involved is related to the level of details required by the customer and on the identified critical disciplines.

The design process and iterations are directed by a *Team Leader* or Facilitator. An effective team leader is usually an expert system engineer with skills in human resources management. The team leader should be able to manage the design process dynamically and in real-time, understanding the maturity of the design while motivating people and maintaining a fast turnaround.

2.4.3 Open Concurrent Design Tool

The approach given by the IDM had limitations, especially when scaling to more complex systems and when considering the whole system lifecycle. Hence a more flexible and effective tool has been developed.

The new developed tool, namely Open Concurrent Design Tool (OCDT), has a modern client / server architecture involving a database management system to enhance data sharing and design interoperability (Figure 21)

In order to create an interoperable and standardized environment, OCDT implements the conceptual data model defined in ECSS-E-TM-10-25[58].

OCDT is based on modern Model Based Systems Engineering approach and involves user functionalities in order to allow team members to create, modify and delete a parametric engineering model of a space mission. To avoid any misunderstanding regarding the parameters, any value of each parameter is in charge of a single domain of expertise. Nonetheless, a team member may use any of the parameters owned by other domains as an input to his/her part of the engineering model by "subscribing" to it during the design sessions.

OCDT has a service-oriented architecture decomposed in three layers. Each layer is composed by a set of specific software modules that address a specific set of functions enabled in the tool. The layers, pictured in Figure 21, are:

1) A persisted design data database developed in PostgreSQL®;

2) ConCORDE (Concurrent Concepts, Options, Requirements and Design Editor), the graphical user interface fully integrated with Excel providing the following functionalities with respect to the final user:

- For concurrent design team members: Creation, modification and erasing of requirements, parameterized design concepts, reference unit of measure and in general design data, options and trade-offs.
- For model managers: Set-up and management of participants, permissions, model organization.
- For site administrators: Management of user account, rights and permissions, , backup and restore of data, server configuration.

3) Web services layer based on NodeJS®

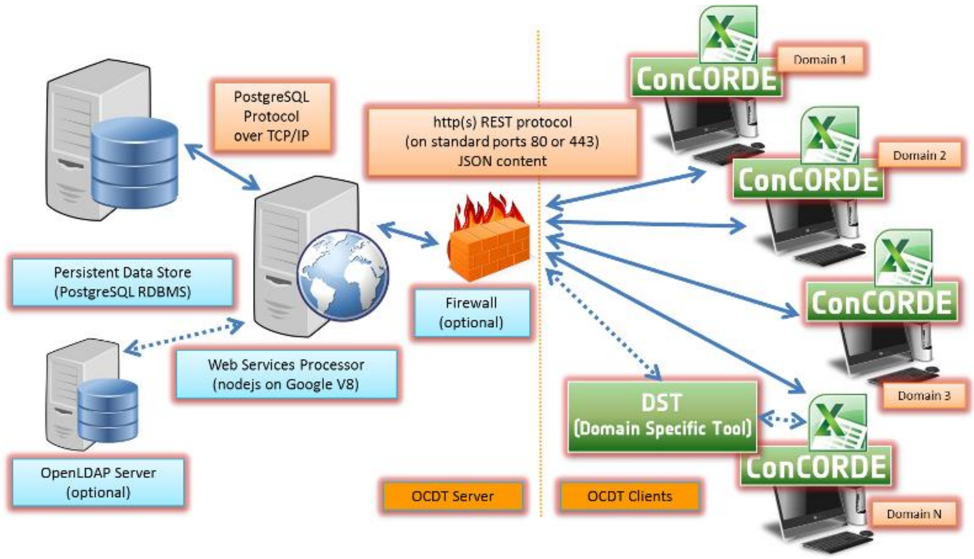

Figure 21 Schematic overview of the OCDT architecture

2.4.4 The facility

The design team works in the Concurrent Design Facility (CDF), located in ESA ESTEC.

The facility comprises a main design room plus a project design room and a support design room. The development of the CDF was driven in order to facilitate the design process by enhancing interaction, co-operation among team members. The disciplines highly interfaced, are located close to each other in order to stimulate the iteration process while keeping it structured. The set-up can be redesigned with different layouts and active disciplines depending on the specific mission under study.

At the front of the facility, large projection screens are used to project the display of each workstation in order to allow discipline expert to present design options or possibly proposals, highlighting any effects or drivers imposed on, or by, other domains. Video conferencing equipment is also installed to allow team members to participate in sessions from remote sites.

2.5 Review of Concurrent Engineering approach at Jet Propulsion Laboratory: Team X/Team Xc

JPL based Team X is an advanced concept design team for the real first application of concurrent engineering for space mission concepts development.

Team X was established in 1995 to address the need to create and evaluate many mission concepts in a short timeframe, nowadays it is considered as the NASA's original concurrent engineering team. To fulfil the latter needs, 2 principal characteristics has been implemented:

- Networked subsystems compute real-time design changes involving the principal investigator during the design iterations
- Data and information sharing across subsystem disciplines in order to facilitate identification and resolution of issues and trades

The team was and still is composed by around 20 discipline experts at mission system and subsystem level.

Like in the ESA CDF organization, not all the experts are only assigned to Team X activities and not all the disciplines are evaluated in all the studies, but the selection is done in function of the type of mission involved in the study session.

In 2013, JPL's Innovation Foundry began the development of a Team X derivate Team Xc in response to the emerging need for developing innovative CubeSat, NanoSat, and Small Satellite concepts. An average Team Xc study last two weeks with two study sessions and costs the equivalent of one work-month of a full-time employee [59].

Team Xc's activities are executed according to the Concept Maturity Level (CML) scale [60] (See Appendix form mode detailed information). In specific, from feasibility assessment (CML 2), through trade space exploration (CML 3), point design selection (CML 4), and high-level baseline concept review (CML 5). These tasks are tailored to provide the following goals in each CML push:

- ***Feasibility Assessments (CML 2)***: CML 2 studies are essentially aimed to answer the question: "*can my mission be executed with a CubeSat, NanoSat or SmallSat?*" At the kick off, the customer provides a high-level overview of its needs including a short description of the payload/service to be demonstrated. The team then assess the feasibility of the mission concept within the known constraints and capabilities such as mass, power, volume, CubeSat design requirements, etc. During CML 2 studies, subsystem experts use reduced but rapid design tools to evaluate a first-order sizing calculations evaluating initial feasibility of the concept. Additionally, the team identifies key issues and challenges for the customer to be tackled as the concept matures.

- ***Trade Space Exploration (CML 3)***: CML 3 studies help the team and the customer with the high-level exploration of both mission and systems architectural alternatives. Before to the study sessions, the systems engineering team, composed by team leader and system engineer, identifies and analyze the trade criteria with the customer setting up the attributes to be used to explore various trades within a fixed number of design sessions (*typically 2 or 3*). During the iterations, quantitative and quantitative analyses are evaluated aiming at assisting the team in the selection to the most effective alternative. Two mission concepts and architectures that can then be forward analyzed in a CML 4 study are typically selected.
- ***Point Designs (CML 4)***: CML 4 studies provide to the customer a selection of a point design. During the planning session, the team identifies the technical domain(s) in which pre-study work needs to be done such as trajectory design or preliminary configuration. In addition to CAD design, a 1:1 scale of a 3D printed spacecraft to be exhaustively used during review sessions can be developed.
- ***High Level Baseline Concept Review (CML 5):*** CML 5 studies provide the customer team with a detailed review of their solution, with particular focus on management and schedule, flight system design, instrument design, science investigation design and operations, and cost. Risk analysis and a set of major and minor weaknesses to iterate towards enhancing their concept are also presented.

Chapter 3

Ladybird guide to agile concurrent engineering and application to academia

In this Chapter, we will go through the application of the Concurrent Engineering approach within an academic environment, trying to answer to the research question:

Q1: Would it be valuable to adapt the concurrent design approach within the academia? Would it be beneficial in terms of learning effectiveness? How can industrial approach be tailored to academic porpoise?

In particular, a tailored methodology, including tools, processes and methods, has been developed and will be analyzed. Challenges and lessons-learned will be summarized with the goal of giving a high-level overview of outcomes obtained by the successful application of CE within an academic environment.

The developed methodology, named Agile Concurrent Engineering, has been developed in order to tackle issues and constraints given by a CE team composed by students. Nonetheless, it resulted suitable also for expert-based CE sessions, assisting in standardizing design sessions and tools, and speeding up the iteration process.

3.1 General description and introduction to Politecnico di Torino concurrent engineering facility

Several studies on Concurrent Design were carried out since 2000, within PhD researches carried out in collaboration with ESA/ESTEC CDF and Thales Alenia Space. During the last 3 years, a follow-up development and integration of the CEF infrastructure has been finalized, within the activities of this research. The integration among infrastructure and design approach tries to merge the lessons learnt from both ESA CDF and the JPL TeamX activities, adapting those approaches for academic purpose. The current goals are: (i) to improve effectiveness of systems engineering in educational activities; (ii) to provide complement to system engineering curriculum; and (iii) to provide introduction and education skills on systems engineering and on the Concurrent Design approach.

Development drivers have been derived from ESA CDF, JPL TeamX/Xc, students' needs and from the lessons learnt by the application and development of concurrent engineering facility by Golkar et. al. [61] . These drivers can be summarized as follows:

1. Understanding needs of students and developing a low-cost CEF, with flexible schedule;
2. Designing infrastructure and tools according to university constraints, such as rapid team turn-over;
3. Tailoring the approach for reconfigurability, upgradability and maintainability;
4. Fostering Concurrent Engineering approach and providing clear understating of its scope with a demo study.

The Politecnico di Torino CEF has been developed aiming modularity and flexibility, targeting students who wants to learn and experience the Concurrent Design Approach, all tighter in the very same room, but also allowing their training exploiting tools and models without constraints. Data exchange is based on OCDT, compliant to ECSS-E-TM-10-25A [58] and it is firstly carried out via Ethernet connection. Moreover, to fulfil the objective of modularity and flexibility, it is also guaranteed via WI-FI connection without additional firewalls. This approach allows students to connect their laptop to the central data repository, which constitute the central node for the data exchange system. The central facility also contains one projector and one 47 inches monitor to guarantee continuous sharing of design data and concept maturity during the design iterations.

CEF relies mainly on students to carry out projects. Students are enrolled in MSc or PhD programs and their number varies from small teams of 4 students for pre-studies up to 25 students during actual CE sessions. In the latter case, students are split into focused teams, depending on their background and attitude. Study leaders are mainly doctoral students. Next Sections provide a thorough overview of the proposed approach, process, methods and tools.

3.2 Team and sessions management

In this Section, the developed design process will be introduced. This process has been developed according to the identified needs and constraints related to students' activities and based on feedbacks from test design sessions. In particular, it was important to take into account the following drivers:

- Short learning curve, lack of knowledge, thus need of fast knowledge generation and consolidation;
- Sessions synchronized with academic schedule;
- Faster team turnover compared to industrial standards.

Trying to overcome these issues, an agile management methodology has been adopted, focusing the attention on team-building and team-management due to the strict constraints characterizing an academic concurrent engineering facility, such as busy students schedule and lack of knowledge.

3.2.1 Design process: Proto-spiral model and adaptiation of Agile project management

As previously introduced, the design process is strongly influenced by both ESA and JPL TeamX approaches. In particular, the main goal aimed at harmonizing the integration of Concept Maturity Level with the already validated spiral model presented in section 2.4.1. Moreover, trying to obtain a faster and more educative process, a model-based approach, i.e. virtual model and additive manufacturing techniques, has been exploited aiming to modify the pure spiral model[54] according to the prototype one, thanks to the exploitation of virtual and reduced prototypes (see section 4.4.2 for more details about virtual and reduced prototypes). Here, prototype is defined as an operational model of the application system, implementing certain aspects of the future system. Protypes provide a concreate basis for discussion between students and "stakeholders", discussing difficulties and assisting the generation and iterations of requirements. Prototypes also serves as a basis for follow-up applications and development of the system, helping students to gain experience and knowledge about the mission under analysis.

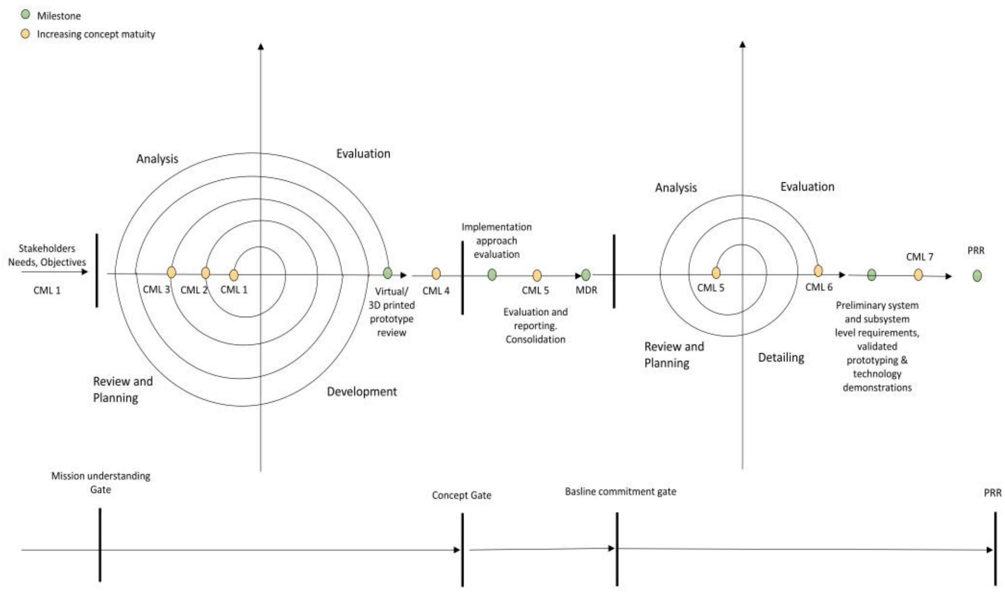

Figure 22 Proto-spiral development model for agile concurrent engineering

The proto-spiral model exploited for the study sessions tries to standardize the target number of sessions needed to push the maturity of the concept from one level to the next one. According to the spiral model, during every iteration each mission driving parameters is analysed and evaluated concurrently. Models improvement, development and advancement or issues are documented in order to evaluate a plan for the following session thought adhoc developed toolset.

The formal "pass" of the CML to the next level is given by four main review gates, in which the systems engineers team, concurrently with the design team, evaluates the actual feasibility and goodness of the study. This approach is also able to give to the students the ability to understand any open issue and where to focus more their attention. Figure 22 provides a thorough overview of the process, in terms of concept maturity level, expressed by number of iterations, goals, when applicable gate and review methods.

From pre-study to CML 1: Mission definition SE session

- *Activities\Goals*: To identify stakeholder needs, type of observations needed for fulfil the needs, and a scratch idea of the mission concept of operations and high-level objectives have been formulated;
- *Iterations needed*: Pre-Study Phase, typically one iteration;
- *Gate*: Mission understanding gate, reviewed with product owner and initial feasibility based on similitude with past missions;
- *Corresponding ESA review*: None.

Session 1: Kick-off to CML2

- *Activities\Goals*: To deeply analyse the stakeholder idea based on technical feasibility, from a science, technical, and programmatic viewpoint. Deriving lower-level objectives, identification of mission drivers, with desired values based on analogy. Basic calculation for critical discipline, e.g. payload FOV analysis, raw orbits analysis;
- *Iterations needed*: One iteration with the support of systems engineering team;
- *Gate*: None;
- *Corresponding ESA review*: None.

Session 2: Start of design to CML3

- *Activities\Goals*: To identify architectural alternatives and exploration with respect to mission objectives. To perform analysis between the space segment, ground and orbit design to evaluate impact of changes increasing knowledge about design variables;
- *Iterations needed*: One iteration with systems engineering team;
- *Gate*: None;
- *Corresponding ESA review*: None.

Session 3-4: end first iteration CML4

- *Activities\Goals*: To select specific proposed architectures set (max 2) within the tradespace. More detailed analysis to the level of major subsystems with acceptable margins and reserves. To develop a preliminary concept of operations for the mission, Master Equipment List (MEL), Power Equipment List (PEL), power modes, orbit/trajectory design, high-level mission cost range, science/mission requirements and traceability, schedule or project timeline, link budget, identification of ground stations, identification of heritage missions and/or components, and structural design, development of virtual and 3D prototype model;
- *Average iterations needed*: three iterations;
- *Gate*: Concept gate, assessment on concept feasibility and comparison with mission needs, exploiting of prototypes for team review with possible minor modification through evaluation of measures of effectiveness and performances;
- *Corresponding ESA review*: None.

Session 5: consolidate solution, knowledge transfer to CML5

- *Activities\Goals*: To define implementation approach, integration and test approach, final concept consolidation with respect to programmatic;
- *Iterations needed*: One iteration plus final consolidation meeting;
- *Gate*: Base line commitment gate, validation and verification of preferred baseline design against stakeholder needs;
- *Corresponding ESA review*: Mission Design Review (end of Phase 0)

In case a more detailed analysis is needed, the proto-spiral model is then repeated to increase the maturity of the concept towards CML 7, preparing for the final preliminary requirements review (PRR) in order to validate the feasibility and goodness of the selected baseline. The follow-up iterations after the baseline commitment gate are planned to be more topic-focused, based on the criticalities highlighted in the previous CML. Since it has been assumed that, at least at system level, the design is robust enough, less iterations are needed to push the CML towards level 7, avoiding excessive time loss while passing to the subsystems preliminary design. Moreover, the last iterations are also dedicated to the validation and enhancement of developed prototypes.

Going into details with the sessions management, an AGILE project management techniques has been adopted, whose perfectly fit with the aforementioned spiral model design approach, but tailored for aerospace project management as suggested by Darrin et.al. [62]. Indeed, the Agile Program and project management have been studied for managing agile software projects and more recently they have been also tailored for aerospace program management. Agile management is described in [63] as follows:

"*…an iterative, incremental method of managing the design and build activities of engineering, information technology and other business areas that aim to provide new product or service development in a highly flexible and interactive manner; an example is its application in Scrum, an original form of agile software development.*"

Agile program management is appropriate for programs and projects where the level of uncertainty is high, for example in high technology projects, especially during the early design phases. The mantra of the Agile program management can be summarized by its manifesto (see appendix

C: Agile Project management Manifesto). In literature, there are several approaches to adapt Agile project management and several examples are given by XP, Lean programming or Kanban ones as described in [64].

For the application of Agile project management within the proposed concurrent approach, the Scrum approach has been adopted, exploiting the planning and control functionalities offered by the open source application named Trello®. Classic Scrum starts with the identification of *Product Owner and Scrum Master*. The Product owner is the person who represents the final user's best interest and has the authority to say what goes into the final product. That Product Owner oversees the tasks related to making the *backlog*, a list of tasks and requirements needed by the final product, which must be prioritized. On the other hand, the Scrum master is the person who helps the team moving along each Scrum, fostering pro-active attitude.

Next up is the Sprint. A Sprint is a predetermined timeframe, within which the team completes sets of tasks from the Backlog. Each Sprint ends with a review, or Retrospective, where the team reviews its own work and discusses ways to improve the next Sprint.

Going into details with the tailoring of the Agile approach within the concurrent engineering session, hereby roles and session management are analysed in the follows. The function of Product Owner and Scrum Master are handled respectively by the systems engineering team and the team leader, whose must be identified in PhD students or academic professor due to their higher technical and management experience. The preparation of the sessions is carried out, by exploiting the backlog concept in Trello® as pictured in Figure 23 and public accessible at https://trello.com/b/3qACa1NA. In particular, the set-up for the backlog is composed by the list of everything that is needed for the project, ordered by importance. It is important to underline that, as the project takes shape, new needs and drivers might emerge. It is responsibility of the systems engineers to manage the backlog and update it, following the sessions advancement. After practical application of this approach, the final version of the backlog is composed by the following list of items:

- *Session backlog*: in this board, high-level requirements and constraints to be analysed during the current session are reported, with prioritization. This board is in charge of the systems engineer but resulted useful also for the design team in order to keep track and understand the tasks relative to each session, working on the most valuable tasks.

- *Mission backlog*: here are reported all the mission high-level requirements and functions to be added to the mission under analysis. It serves as back-up for the session backlog and offers a traceability between design sessions and mission needs.
- *Iterations archive/ resources*: this board is aimed at assisting during the execution of the design sessions, modelling the proto-spiral model. Each board summarizes the tasks needed to push the maturity of the design and the team composition of each session must be allocated to the relative board. Presentations, reports and possible models are attached to the relative task guaranteeing the traceability between tools and tasks. Thanks to this board, the team is thus able to track the advancement of the project. It also helps students with the understanding the whole project tasks.
- *Discipline maturity*: this board is managed by both systems engineers and discipline expert, to evaluate the maturity of their design, from concept to preliminary design. It helps the team leader and systems engineers to keep track on the advancement of each discipline, assisting the iterations over the sessions. This board also help students in the execution of their discipline study.

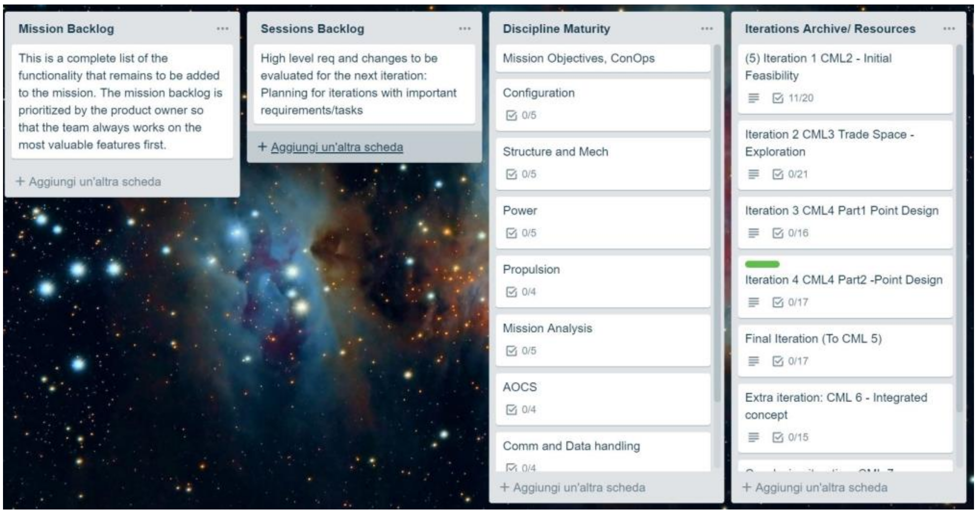

Figure 23 Agile session backlog set-up (https://trello.com/b/3qACa1NA)

The assistance in the definition of the discipline, related tasks, and the corresponding design maturity is given by the new developed tool named Discipline Maturity Chart (DMC). The DMC is iterated at the beginning of each session, helping in reviewing and iterating the discipline tasks and its maturity by a brainstorming carried out by the whole team.

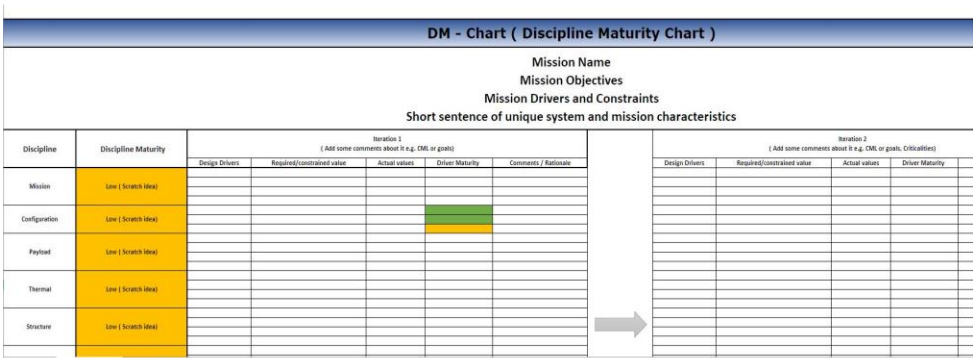

Figure 24 Discipline Maturity Chart

The DMC showed in Figure 24 is managed by one system engineer and is structured in order to support brainstorming sessions and to track discipline maturity throughout the design. It incorporates high-level description of the mission in terms of mission name, objectives, drivers, constraints and mission uniqueness. During the core of the session, the DMC is continuously presented to the entire team in order to keep all the members informed for any advancement in all the disciplines, in parallel to OCDT, while recalling high-level drivers of the mission development.

For each discipline a list of design drivers and required/constrained values must be derived, and the actual value is than associated with a tag in the OCDT. Thus, the system engineer is able to evaluate the maturity for each discipline parameter and to assess an overall maturity for the discipline under analysis. Hence, according to the team leader, i.e. the Scrum master, it is possible to control single discipline maturity by identifying and guiding criticalities within the mission design. During the evaluation of the DMC, the complex nature of mission design might be underlined and students are able to observe and learn the strong interconnection between disciplines, while understanding the importance of negotiation and collaboration among shared design drivers.

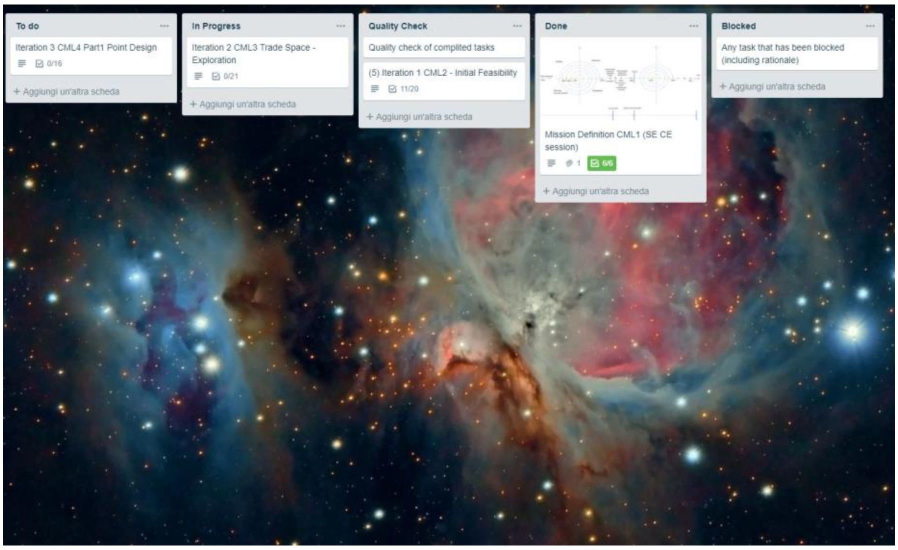

Figure 25 Scrum and Sprint Management on Trello® Board.

Once a session is near to its closure, the modelled boards summarized in Figure 25 are exploited to control and to monitor the status of the study. Pre-planned activities throughout the design sessions are placed in the "To do" board and moved to "in progress", when the team is working on the relative CML push. Once a CML push is completed, the task, concerning all the attachments and comments, is moved in quality check. This entails a final check by the system engineers in order to validate the results obtained. Any comment or modification is added to the task list and a direct allocation (tag) to the owner is placed. This helps not only the students but also the experts to keep track of any comment, issue or information about the study itself.

Once a quality check is passed, the task is finally moved to the "done" board, entailing the conclusion of the task and an advancement in the concept maturity level. Last, for traceability and learning reasons, a "blocked" board has been added, in which all the function and/or whole tasks that was initially required but have been stopped by the systems engineering team are placed. This choice has been made to ensure also that the team will not spent too much time by working on already evaluated tasks.

Summary of agile design sessions and typical schedule

For the proposed approach, half-day sessions of about five hours are envisioned, considering session breaks and sessions retrospective.

The single design session (Scrum) is structured following the tasks in Table 1. For each time slot, a dedicated tool has to be used, depending on the maturity of the mission under study.

Table 1 Agile Concurrent engineer: typical iteration schedule

Activity	Timing	Tool
Sprint Planning Meeting: at the beginning of each session, a planning meeting is held to discuss the work that has to be done. The principal investigator and the team meet to discuss the highest-priority items on the product backlog. Team members figure out how many items they can commit to and then understand the backlog.	30 min Note: based on CML	Science traceability matrix Discipline maturity chart Requirements tool Trello backlogs
Daily stand-up: each day, during the sprint, team members share what they worked on the prior day, will work on today, and identify any impediments. Daily scrums are used to synchronize the work of team members as they discuss the work of the sprint. The first iteration this time is dedicated to the review and understanding of the calculation sheets.	30 min Note: if necessary, from the 2^{nd} /3^{rd} iteration	Trello Backlog and blocked tasks Discipline maturity chart Calculation sheets
Daily design session:	180 min Note: including 20 minutes of coffee break	Calculation sheets DMC Requirements tool
Sprint Review: at the end of a sprint, the team demonstrates the novelties added during the sprint. The goal of this part is to get feedback from the primary stakeholder and any users or other stakeholders who have been invited to the review.	30 Min	Presentations Trello
Sprint Retrospective: at the end of each session, the team participates in a retrospective part to reflect on the sprint that is ending and identify opportunities to improve in the new sprint.	30 Min	Trello to keep notes and add tasks to backlog/Quality check
Total session time	**5 h**	

3.2.2 The Team: building and managing a multidisciplinary team

In Section 2.3, it has been highlighted that the principal ingredient of a successful concurrent engineering session is given by the team that carried out the study. For this reason, this research investigated also the receipt to build and manage a design team. In this Section, the main findings of this analysis are reported. From the psychological point of view, Figure 26 shows the key ingredients and products of a successful team. The vertices of the triangle show the products of a successful team. The sides and inner triangles describe what it takes to make the results happen. In *The Wisdom of Teams* [65], Katzenbach and Smith stress out that the performance of the team, also concerning commitment, is essential for the team success. In particular, they evaluate a definition that distinguishes a real team from "*a mere group of people with a common assignment*".

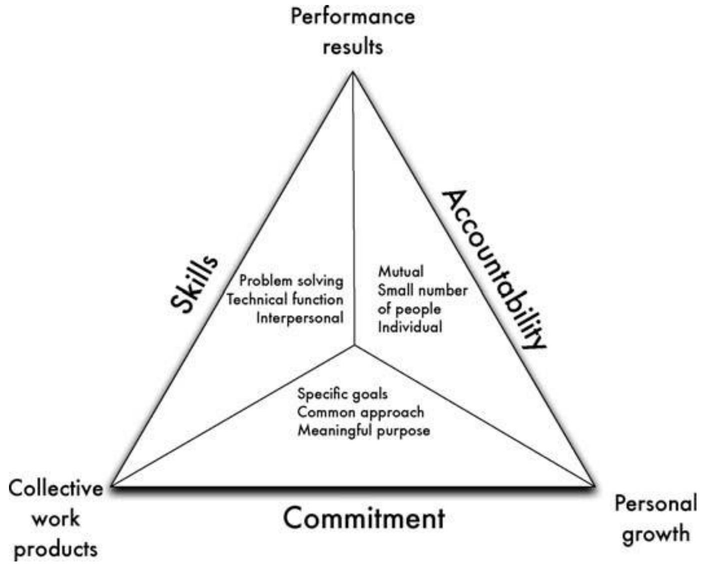

Figure 26 Successful Team ingredients [66]

A team can be defined as a small amount of people with complemental skills, who addresses a common purpose and approach for which they acknowledge themselves reciprocally responsible. Each member of the team has to perceive and follow the answers to the following questions, which define the nature of the team:

1. Why are we here?
2. What are we going to accomplish?

3. What does success look like? How will we know when we get there? The attitude of each team member must be stimulated to follow the mantra “only the team can succeed or fail”. It is important to never forget that *a working team counts on the sum of the individual performance*. Members who share information, best practices, or perspectives to make decisions are indeed helpful to everyone, in order to effectively provide their contribution within their own domain of expertise. Moreover, in order to encourage cooperation and a sense of ownership to each team member, it is advised to constitute the complete team at the beginning of the project rather than involving new members during the development of the project.

Building and managing a performant team requires that the lead system engineer and the team leader have to take many decisions. In particular, the answer to the following questions constitute some of those decisions:

- What is the correct set of skills required and what is the correct distribution of decisional power within the team?
- What are collaboration and problem-solving skills required?
- What is the required problem details in order to fully engage all of the team members?

Nonetheless, due to the uncertainties related to human beings, system engineers must iterate the team structure by analyzing the impact of the team as it goes through the mission under analysis. In this sense, it is recommended to exploit the team performance curve shown in Figure 27 with the goal of exploring the quality of team performance with respect to project goals.

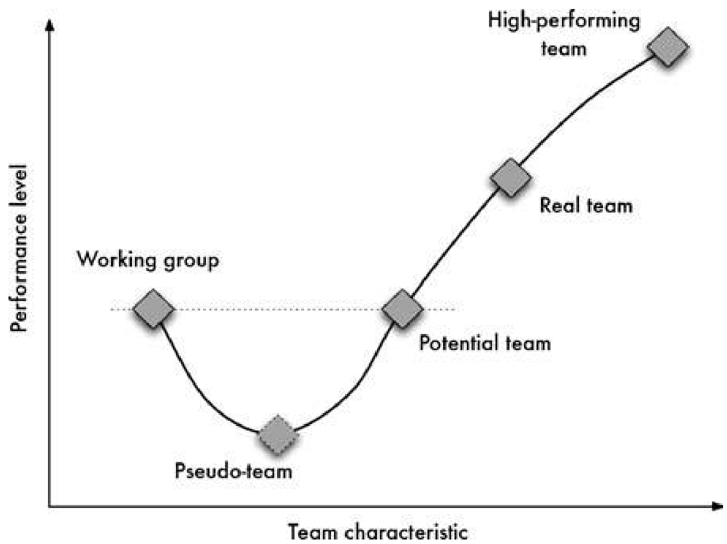

Figure 27 Team performance vs team characteristic [66].

When analyzing the latter figure, it is possible to observe the presence of a low-performance team, i.e. namely the pseudo-team. Pseudo-teams can be identified as teams in which members are not focused on the common and joint performance. Their performance level is indeed lower than the one corresponding to working groups in Figure 27, because the activities of pseudo-team members are more likely constituted by solitary performances without adjoined value for the whole team. On the other side, potential teams have higher performance, even if they cannot be considered as fully mature, but they are towards improving their impact. However, team members have not yet consolidated the "joint performance attitude". Real teams converge to the proper definition of team, provided at the beginning of this Section and they are characterized by higher level of performance with respect to previous teams. Last, high-performance teams have the highest performance level thanks to the extraordinary effort the members put in one another's growth and success.

Before concluding, another sensitive topic to be addressed with respect to the team composition is related to the presence of people with different ethnic, national, or religious cultures. Indeed, these "multi-cultural" teams are becoming more and more ordinary, also thanks to the capability to communicate and interact only electronically, which gave the origin to the so-called "virtual teams". It is evident that also men and women with the same cultural background might behave differently from expectations. Misunderstandings can be created if a team is not trained in working with members from different cultures. Hence, it is important to be aware of the potential misunderstanding in order to avoid these kinds of problems within the team. In general, it is important to keep a spirit of patience and understanding towards team members and, most importantly, being a good listener.

3.2.3 Systems engineers and team leader perspective

When a well-constructed team is involved within a Concurrent Engineering session, it is important to underline the importance of two key actors: on one side the Team Leader and on the other the System Engineer. For each CEF Study, these two actors are key-members in understanding how to handle different personalities, thanks to appropriate communication approach. Learning about how to properly communicate requires attention to the dynamics of social interaction, cultural sensitivity and understanding of the organizational structure. Moreover, more effective communication in the working environment goes a long way in reducing stress, improving interpersonal skills, building trust and getting more things done with less frustration.

The design process is typically guided by the Team Leader, who is supported by a System Engineer and a System Assistant. Apart for the technical challenges, team dynamics and team interaction is the value for success.

The Team Leader and System Engineer require additional "soft skills" in order to:

- Detecting the communication style of everyone in the team;
- Creating a "safe" and "supportive" environment during the sessions so that everyone feels valued, appreciated and involved in the design process;
- Enabling the team to highly co-operate, trust and share information "in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle" as stated in [54].

In "Why Him? Why Her" [67], Helen Fisher explains that variations in human personality are associated with two fundamentally different types of attribute: character and temperament. In general, it is possible to identify four types of personality: The Explorer, the Director, the Builder and the Negotiator.

The Explorer

Explorers are curious and creative, they possesses an intense energy and spontaneity, they are often impulsive. They have a self-reliant mix of enthusiasm, quick thinking and they feel comfortable with uncertainty and they are minimally concerned with preparation. They can get easily bored when not absorbed in something that intrigues them.

The Director

Directors are goal-oriented, and they tend to focus intensely while working. Unlike the Explorers, who focus on a wide range of interests, Directors concentrate narrowly and deeply. Directors foster themselves on being analytical, logical, direct and highly pragmatic.

The Builder

Builders tend to be calm and self-confident, with a high respect for authority and loyalty. Builders also like rules, feel comfortable in hierarchies, where duty and loyalty are required, and structure, rules and order reign.

The Negotiator

Negotiators see the big picture: they think contextually, holistically, synthetically. They have the ability of "web" thinking, not straight lines: during the collecting data process, they think, weight the importance of each variable and determine the relationship among them. Negotiators are highly imaginative, which is very different with respect to creativity.

Being able to master different communication styles, to detect them and to react accordingly is an essential set of skills. Different communication types process and communicate information differently. Under these circumstances, adaptability is key for the Team Leader and System Engineer for a successful CE session. The added value is encouraging the strengths of each team member and approaching him/her in a way that resonates with his/her personality. It helps also to be aware of the team members' personal limitations and challenges, so that it does not get in the way of maximizing team performance and team efficiency in the timeframe of the study, as described in [68]. Table 2 summarizes a good approach to manage different personality types during an efficient CEF study.

Table 2 Communication behave strategies in a CEF study [68].

Personality type	**Typical behave**	**Communication strategy**
Explorer	Curious, daring, expressive, impulsive, innovative, unpredictable, unstructured	Be real, be new.
Director	Assertive, authoritative, convincing, focused, efficient, verbal	Be brief, be brief, be gone!
Builder	Accurate, complete, consistent, controlling, detailed, methodical, thorough, traditional	Be prepared, be tried, be true.
Negotiator	Agreeable, empathetic, expressive, flexible, responsive, understanding	Be available, be supportive, be relational.

Last but not least, the System Engineer shall also be able to understand when it is time to call the design cycle off, observing the reached convergence. Generally, it is possible to adapt the technology maturity S-Curve in the context of design maturity, obtaining the curve pictured in Figure 28.

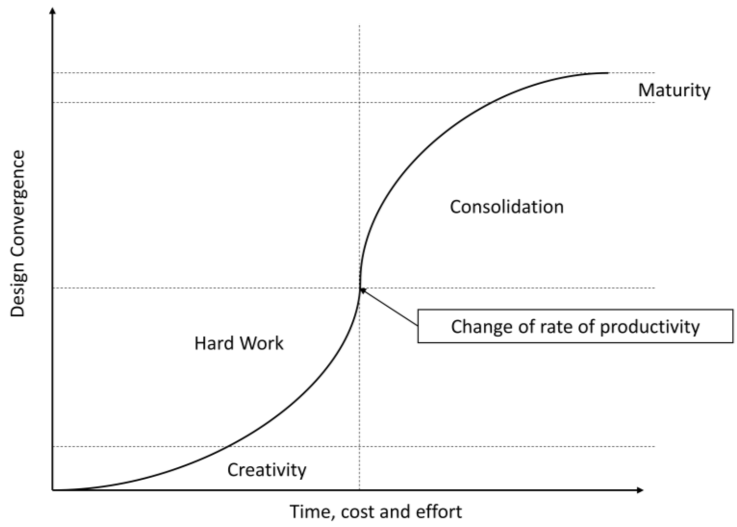

Figure 28 The Design Convergence S-Curve

After a certain maturity, the iterations achieve only marginal improvements to the design. This point is characterized by a change of rate of productivity within a given time and effort by the design team. After this time, the system engineer and the team leader should be able to change the attitude of the team from hard work, which is based on creativity, to consolidation of the studied design, reaching the final convergence of the solution design.

Concluding, properly managing a team, even and especially in an industrial and academic environment, is one of the keys of a successful CE sessions.

Pit Stop

Application of social science, on top of the technical expertise required, is an essential part of the concurrent engineering approach process where cooperation, collaboration and effective communication are defining the way we talk to each other and the way we work with each other.

3.3 Software and infrastructure

The software infrastructure that has been chosen to support the design is the ESA OCDT framework, in which any modification applied followed the ECSS-E-TM-10-25A standard reported in [69]. On the other hand, Excel has been chosen as primary user-interface due to the spreading of the Microsoft tools in both academia and industry. Table 3 summarizes the Politecnico di Torino CEF software architecture, in which, whenever it is possible, open source software have been preferred.

Table 3 Polito CEF: Software infrastrutture.

Software support	**Function**
ESA OCDT ®, RHEA CDP4®	Data exchange and traceability
Microsoft Office Excel® 2010	Models, OCDT interface
AGI System Tool Kit®	Mission analysis
Mathworks MATLAB® R2015a	Interfaces and trade-offs assistance
Dassault Systèmes SolidWorks®	CAD
Thales Alenia VERITAS/ Blender®	Visualization and VR
Cloud directory	Repository
Trello®	Project Control

3.4 Adopting concurrent engineering tools to academia

The goal of this section is to introduces the concepts of adopting and tailoring CE tools within an academic environment, aiming at improving the learning and design experiences offered by the Concurrent Design Approach. Enabling the Polito CEF data exchange functions via both the Ethernet connection and WI-FI with only proxy restrictions resulted in a reliable solution to achieve this goal. Thanks to this approach, the CEF team is able to improve their skills and explore the engineering models from their laptops without location or local ethernet constraints. Sizing tools have been developed as Excel worksheets for each discipline, integrating also Visual Basic macros developed to improve the functionalities of the calculation sheets. The next Sections describe the databases, calculation sheets and requirement management tools developed during this research for the Politecnico di Torino CEF and iterated during a visiting researcher period at the ESA academy. Moreover, these calculation sheets have been made available to all the universities involved in the ESA academy's concurrent engineering challenges, following the ESA academy policy.

3.4.1 Calculation sheets development and adaptation

Design models were developed based on Wertz's Space mission analysis and design [70] and Larson's Cost-effective space mission operations models [71]. The sizing models are applicable to all class of satellites, but particular attention shall be given to peculiar models, e.g. Cost [72], which have been tailored also for Small Sat applications. Component databases were populated for all Nano and micro satellite subsystems, in order to have a gross estimation of design parameters based on fitting of performance data. Moreover, to guarantee a widespread knowledge about all the mission elements, the following database have been developed and integrated into the calculation sheet:

- Small Satellites Mission & Suppliers (1160 Missions & 152 Companies);
- Launchers & Launch Site (104 Active Launchers & 90 Launch Sites);
- Ground Control Stations (260 Elements);
- Payloads (329 Payloads).

The development of the calculation sheets, together with their updates that have been carried out with the intent of assisting students and experts during their concurrent engineering experience, has been driven by the following drivers:

- Flexibility to different mission objectives;
- Flexibility to different satellite class and satellite architecture;
- Standardization of systems engineering tools for all the domain of expertise;
- All systems engineering tool in one file, easier presentation of the results without exploiting Microsoft power point;
- Obtain more quantitative data to:
  - Better understanding the domain of expertise (aimed principally to students);
  - Better communication and negotiation among team members;
  - Better decisions making processes.

The implemented features are presented in the Sections below. Each calculation sheet is mainly composed by the following modules:

- *Introduction and objectives*: a summary of principal discipline objectives and introduction to the calculation sheet (see Figure 29);
- *Sizing and analysis sheets*: discipline related models to evaluate design parameters and budgets;
- *Product Tree*: a dedicated sheet to develop product and/or functional tree;
- *Operative modes*: if the discipline under analysis involves the study of operative modes, a standard sheet linked to OCDT is used to modelling porpoise;
- *Trade-offs*: a calculation sheets implementing an analytical hierarchy process based on parameters prioritization;
- *Discipline Database*: a knowledge database, depending on the discipline it might include components, past mission heritage, ground stations;
- *Constants*: a database of constants used in the arithmetical functions in the calculation sheets.

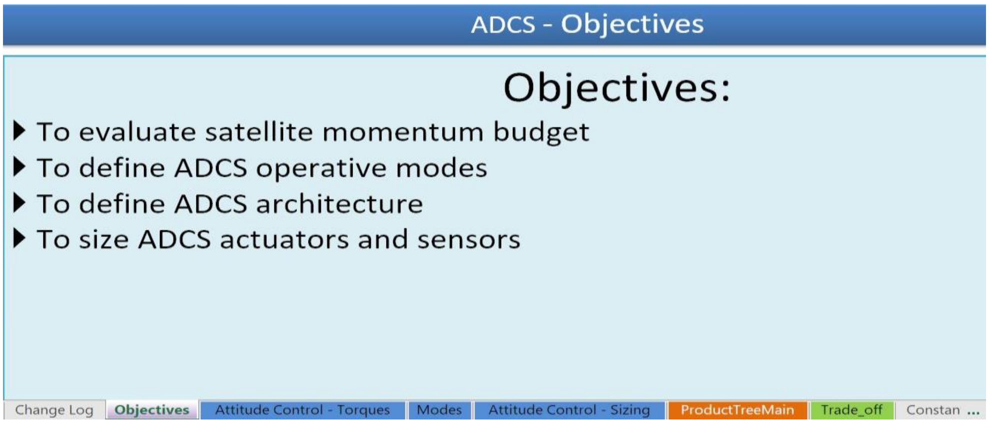

Figure 29 Calculation sheets: Objectives and introduction, an example

In order to have more quantitative data to start with the study session, databases about the heritage in the domain of expertise have been integrated in the calculation sheets, as pictured in Figure 30. The goals related to this integration are the following: (i) to provide more information to the user in order to begin his/her design process for similarity; and (ii) to give more data to communicate and negotiate with the other domain of expertise.

Earth observation missions information

Ref:ITC SATELLITE AND SENSOR DATABASE (https://webapps.itc.utwente.nl/sensor/default.aspx?view=searchsat)

Name	Orbit Type	Orbit Height (Km)	Repeat Cycle (Days)	Organisation
MTI	near polar - sun synchronous	575		US Department of Energy
VENUS	Sun Synchronous	720	2	CNES - France
RASAT	Sun Synchronous	700	4	TUBITAK UZAY/STRI- Turkey
SAOCOM - 1A	Sun Synchronous	620	16	CONAE - Argentina
SWARM	Near polar	530		ESA
QuikSCAT	Sun Synchronous	803		NASA - USA
Svea	near polar - sun synchronous	500		SNSB - Sweden
JERS-1	Sun Synchronous	568	44	JAXA - Japan
SPOT 1	Sun Synchronous	832	26	CNES - France
RISAT-1	Sun Synchronous	536	25	ISRO - India
AlSat-2A	Sun Synchronous	686		ASAL - Algeria
INSAT-2A	Geostationary			ISRO - India

Figure 30 Extension of calculation sheets functionalities: Databases

Additional features have been added to each calculation sheets in order to have a more detailed conceptual design. For example, in thermal calculation sheet, the evaluation of temperature decrease during eclipse has been added through a Visual Basic Marco with a trapezoidal integration (Figure 31). Trapezoidal integrators have been added also to the ADCS calculation sheet, in order to simulate the evolution of disturbance torques along an entire orbit period.

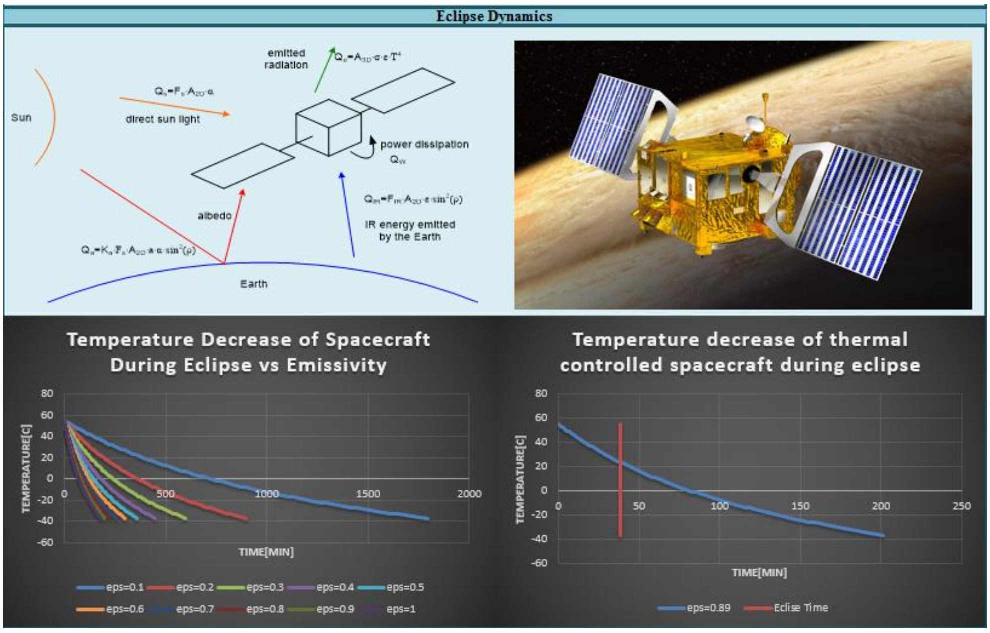

Figure 31 Thermal analysis: evaluation of temperature decreases during eclipse

To enable the flexibility of the calculation sheets to interplanetary mission, the updated sheets incorporate the possibility to select the mission central body and, in case of the mission analysis sheet, the departure and target body, as displaced in Figure 32.

General Inputs	
Departure Body	Earth
Target/Central Body	Earth

Figure 32 Planet selection interface

The consequent effects on the calculation sheets are mainly the following two:

1. Selection of planet constant and sequential characterization of the calculation sheet with respect to the selected central body;
2. Customization of the calculation sheet. In particular, for the mission analysis, the following calculation sheets will be enabled:
    a. Evaluation of interplanetary launch windows (Hohmann transfer approximation);
    b. Interplanetary mission database;
    c. Orbit transfer design (patch conics approximation);
    d. Planet fly-bys.

The calculation sheets also include local alternative exploration, encapsulated within macro buttons. Figure 33 shows an example related to the thermal analysis. The macros will use the data provided by the calculation sheets to evaluate a domain local tradesapce. This is done by varying the domain design variables, and afterwards displays a set of design alternatives. In this way, the user is able to quickly explore different design solutions related to, in this example, the passive thermal control alternatives.

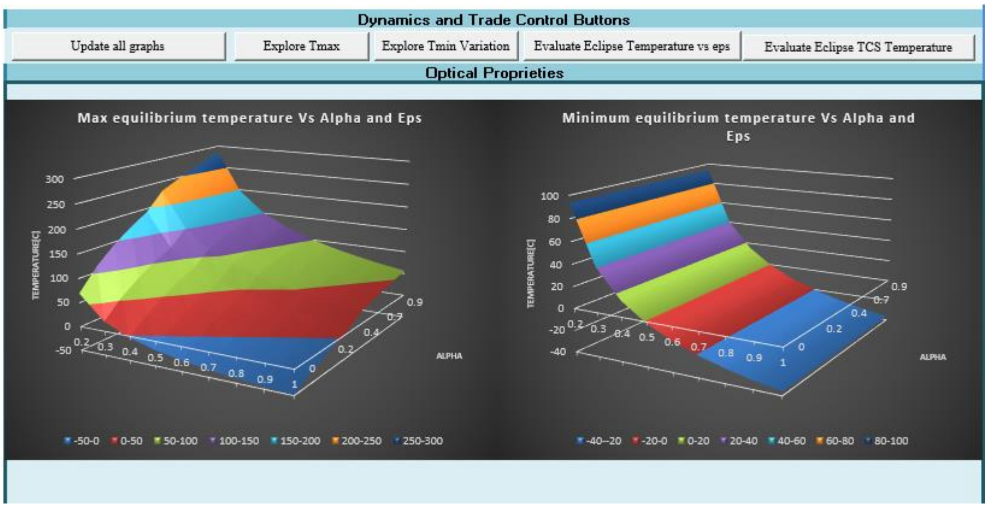

Figure 33 Thermal analysis: passive thermal control trade space and alternative selection.

The trade-off sheet is mainly composed by a weight evaluation based on parameter prioritization, as shown in Figure 34. Furthermore, a radar chart can be used to visually understand the main differences between alternatives, by the analysis of the selected trade parameters, as pictured in Figure 35.

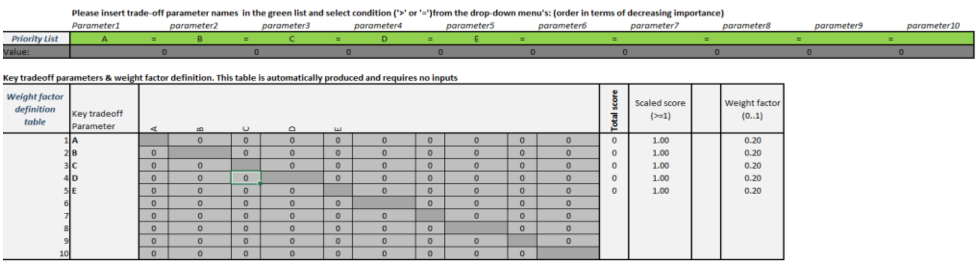

Figure 34 Weighting Factor with prioritization approach.

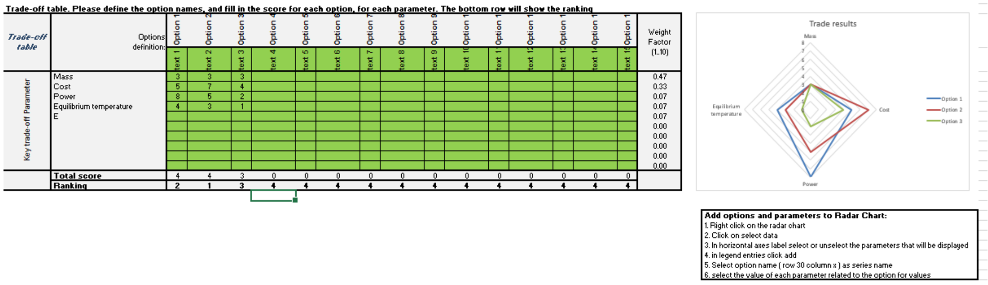

Figure 35 Trade Offs Results and radar chart.

To extend the exploitability of these calculation sheets for CubeSats satellites, the following features have been added:

1. *Thermal analysis sheet*: selection of solar array configuration for body-mounted options;
2. *Structural analysis*: analysis of prism-shape structure rather than cylindrical one, both monocoque and semi-monocoque;
3. *Communications analysis*: antenna design model (monopole, dipole);
4. *ADCS design*: thruster selection and cold gas for attitude control;
5. *General*: equipment mass and power estimation based on fitting of available CubeSat components data.

Further analysis and data gathering for CubeSat components are needed to have a better estimation of subsystems mass and power consumptions. For more details about the developed calculation sheets see appendix D: Politenico di Torino Concurrent engineering facility: calculation sheets.

3.5 Concurrent requirements modelling

The concurrent requirements modelling (CRM) tool is inspired by the ESA IDM architecture and it has been developed in Excel Visual Basic and it is compatible with the versions of Excel® from 2010 to 365. During the design sessions, the domain experts have not only the task of sizing and architecting their domain but they have also to develop and manage domain requirements. The main goals behind the development of CRM are: (i) to better integrate the requirement generation and management process within a concurrent design session; (ii) to standardize the form of the requirements according to ECSS standards [73]; (iii) to assist the design team in the generation and management of requirements; and (iv) to have a faster and better requirement generation and management process.

CRM is composed by 3 main **Excel Workbooks,** represented in Figure 36**,** namely:

- The requirements database;
- The domain expert user interface;
- The systems engineer user interface.

The requirements categories are compliant with the ECSS-E-ST-10C [73] standards.

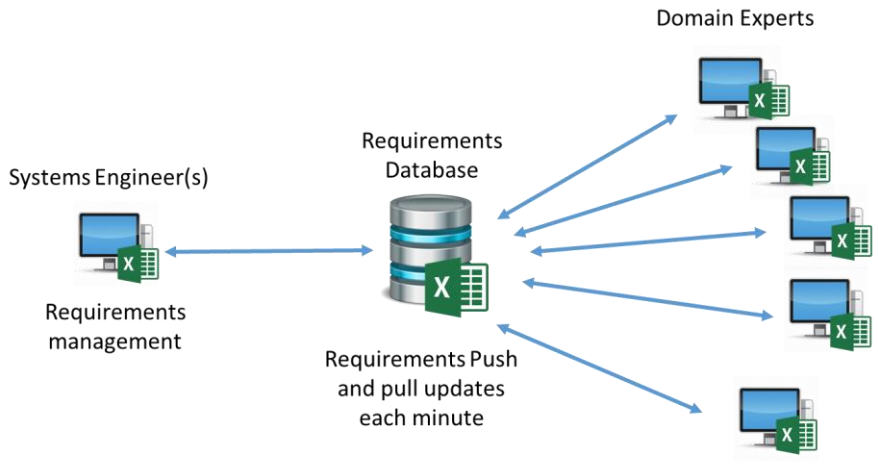

Figure 36 CRM architecture

The CRM tool has been developed to infuse the approach of concurrent design also in the requirements generation and management process.

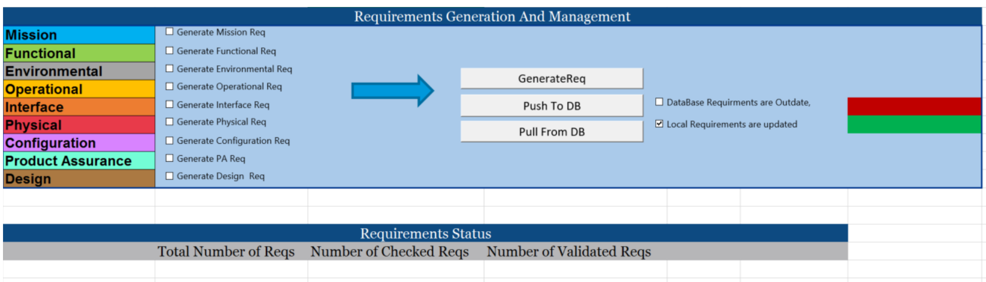

Figure 37 Domain expert user interface

The main control panel, represented in Figure 37, allows the domain expert to generate only the requirements sheet related to the desired category of requirements, e.g. mission/functional, by selecting the requirement type and pushing the “generate requirement” button. When a requirement category is unselected and the generate requirement button is pressed, the requirement sheet will be deleted after a warning message. Navigation among different requirements type is enabled by navigation macros that will be generated with the generation of the new requirement sheet.

To properly define a requirement, the tool involves entries that needs to be filled by the user and other information that will be automated generated by the tool itself. All the characteristics can be filtered to navigate throughout the requirements. Table 4 summarizes the requirement characterization entries.

Table 4 Requirement definition features

Requirement characteristic	**Input type**	**Comments**
Discipline owner	Automatic	Extracted from the first 3 letters of the calculation sheet name, targeted for CE sessions
Discipline Target	Manual	Used to flag a requirement directed to a specific domain of expertise (Systems engineer feature), targeted for CE sessions
Category	Automatic	Extracted from the first 3 letters of the sheet title (first row of the current sheet)
Level	Manual (drop down list)	Definition of the level of the requirements with respect to the system decomposition (system, subsystem, equipment)
Number (#)	Manual	Requirement number for traceability
ID	Automatic	The complete requirement id, generated automatically from the previous information
Requirement text	Manual	The actual requirement statement
Check Status	Manual (drop down list)	Define the review status of the requirement among none, check (checked by the system engineer), validated (validated by the discipline owner/target and system engineer)
Comments	Manual	Additional comments to the requirement
Father ID	Manual (drop down list)	Selection of father requirement (if any) to guarantee traceability
Child ID	Manual (drop down list)	Selection of child requirement (if any) to guarantee traceability (optional)
Verification method	Manual (drop down list)	Selection of requirement verification method according to standards

Systems engineers can manage and control the requirements in real-time during the design sessions via the following features:

- Exploration of number of requirements per domain and per category via navigation macros (Figure 38);

Requirements status				
	Total Number of Requirements	Number of Checked Requirements	Number of Validated Requirements	
Mission Requirements	1	1	0	GoToMissionReq
Functional Requirements	2	1	0	GoToFunctionalReq
Environmental Requirements	1	1	0	GoToEnvironmentalReq
Operational Requirements	1	0	1	GoToOperationalReq
Interface Requirements	1	1	0	GoToInterfaceReq
Physical Requirements	1	1	0	GoToPhysicalReq
Configuration Requirements	1	1	0	GoToConfigurationReq
Product Assurance Requirements	1	1	0	GoToProductAssurance
Design Requirements	1	1	0	GoToDesignReq

Figure 38 High level requirements management interface

- Management of the status of the requirements between checked and validated, in order to track the validation of the requirements per discipline and category (Figure 39);

Active Disciplines [Total\Checked\Validated]	Payload	SYS	MISS	ADCS	EPS	CDH	COMM	STRUCT	THERMAL	PROP
Mission Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Functional Requirements	0\0\0	1\1\0	0\0\0	1\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Environmental Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Operational Requirements	0\0\0	1\0\1	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Interface Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Physical Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Configuration Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Product Assurance Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Design Requirements	0\0\0	1\1\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0	0\0\0
Total Per Discipline	0	9	0	1	0	0	0	0	0	0

Figure 39 Detailed requirement management interface

- Addressing requirements to a domain expert (Figure 40Figure 16).

Discipline Owner	Discipline Target	Category
Sys		MIS

Figure 40 Targeting Requirements to a domain expert

Last, the requirement management process can be summarized by the following algorithm:

Concurrent requirements modelling: Process details

Inputs: High level mission requirement (stakeholder needs)

Output: Domain requirements

0: Systems engineer initiate requirements and dress those to the domain of expertise (Push action)

repeat

For Each domain expert i (in parallel) **Do**

1.0: Pull addressed requirements from database

repeat

1.1: Derive and check domain requirements while designing the subsystem

1.2: Define requirements and select verification method

1.3: Push to server the derived requirements

1.4: System engineer receive notification of new requirements, pull action

1.5 System engineer check and validate the derived requirement and push the updated ones

Until Iteration is finished

end for

2: System engineer final push

until all requirements are checked and validated, design is consolidated

3.6 Summary and international test: First ESA academy concurrent engineering challenge

The developed CEF and the Agile CE methodology have been tested in a first official test case in September 2017, thanks to the precious support of ESA academy. The Polito CEF team, built according to the methods presented in previous sections, had the opportunity to take part in the ESA Academy's first Concurrent Engineering Challenge (ref: https://goo.gl/Q9YMnF). Three European universities, Politecnico di Torino, Technical University of Madrid and University of Strathclyde, have been selected to participate in the challenge in parallel with the design activities in the European space Security and Education Centre at Redu in Belgium. In this challenge, each group of students was then divided into smaller teams, each one devoted to design a different subsystem of the mission, with the assistance of professors and PhD students playing as systems engineers and team leaders (see Figure 41). All three universities shared a common schedule and the Polito CEF design tool, developed within this research, was shared among the participant universities.

Figure 41 On the left: concurrent engineering team, On the right: systems engineering team.

The objectives proposed by ESA were divided into primary and secondary objective mainly focused on the exploration of the Moon as:

- Primary objective: The mission shall make pictures of lunar south pole areas with high expected water/ice content, with a resolution of 10 m/pixel
- Secondary objectives: (i) The mission shall observe the lunar radiation and micro meteorite environment (ii) The mission shall observe the water/ice content of the lunar south pole

Moreover, the following mission constraints have been identified: (i) the total mass of the whole system shall be (at most) 300 kg; (ii) the mission shall remain in Lunar orbit for (at least) 2 years. Each team had five days to complete the activities and finalize the mission and system design. For the PoliTo team, the mission was named “Water Ice South pole Explorer” (WISE) and each working session is described hereafter.

Session 1: Kick-off to CML2

The first session has been dedicated to the analysis of stakeholders and a first technical feasibility analysis has been carried out. The outcomes of the Lunar Exploration Analysis Group [74] have been employed to draw a more detailed and value-centred mission design. The team underlined that recent years have seen a rapid expansion of international participation in lunar exploration. The Moon has become a focal point for many governmental and private organisations in the areas of technology development, scientific research, human exploration and public engagement. Small spacecraft lunar missions, with a significantly lower entry-level cost than previous lunar missions, can also provide a means to building a broad community of developers/users of Moon exploration and growing the pool of skills/experience that will be needed for the larger missions that will follow. The team decided to focus its attention to the ***Shackleton*** south lunar crater, due to the vicinity to the foreseen human outpost. In particular, attention has been given to water/ice content of the lunar South Pole, to support future human exploration of the lunar surface according to the D-7 and B-2 open points identified by the LEAG. During the second iteration of the brainstorming session, the disciplines that were identified as “critical”, such as payload and mission analysis, started to evaluate basic calculations. The outcome of this analysis has been summarized in a Science Traceability Matrix (see appendix

G: Science Traceability Matrix), which guided the team throughout their follow-up design sessions.

Session 2: Start of design to CML3

The second session has been dedicated to the identification of architectural and operational alternatives with respect to stakeholder needs. Architectural alternatives have been initially identified in the space segment definition, specifically: (i) monolithic vs distributed space segment architecture; (ii) transfer strategy in terms of orbit and propulsion technology; (iii) secondary payload among neutron detects, infra-red camera, multispectral imager or distributed synthetic aperture radar. To assist the identification of the most promising target for the observation task and to evaluate the operations of the space segment, in terms of both mission operations and system operative modes, a Virtual Reality environment has been developed. The virtual scenario visualized the illumination conditions over the lunar south pole as displaced in Figure 42.

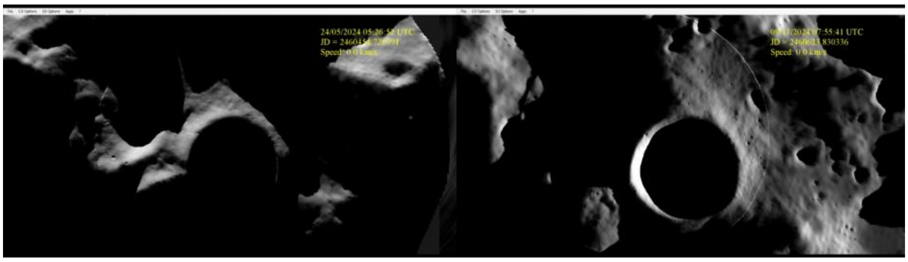

Figure 42 Virtual Reality generated shadowing (on the left) and illumination (on the right) conditions over the lunar south pole with focus on Shackleton crater.

Meanwhile the team started with the discipline exploration of alternatives in order to evaluate the impact of changes in their design. Derived the high-level operative scenarios and settled the alternatives for each discipline, the session has been closed with a final summary and knowledge consolidation of the discoveries. After a first trade-off session, a scratch idea of the mission and the system(s) was drawn, as represented in Figure 43.

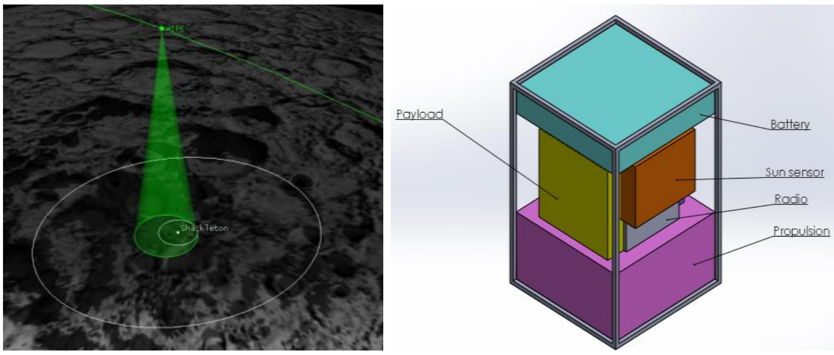

Figure 43 Preliminary mission analysis (on the left) ad system configuration (on the right).

Session 3-3,5: end of first iteration CML4

During the last session, the team focused on the analysis of the proposed set of alternatives. More detailed analysis and a preliminary concept of master equipment list were derived. Trajectories and budgets were iterated towards convergence with stakeholder needs and mission constraints. After a trade-off session, a direct orbit to the Moon has been proposed, to insert the probe into a lunar circular polar orbit, keeping the Weak stability boundary solution as back up for more flexibility in the launch date. After the final iterations, a single quasi-300 kg small satellite has been designed. The system integrates three payloads: (i) a visible camera for south pole visualization; (ii) a spectrometer for soil characterization; and (iii) a passive radiation detector, capable of reliable measurement up to 200 km of altitude, for radiation environment characterization. Virtual models, shown in Figure 44, were finalized in order to verify mission effectiveness with respect to identified stakeholder needs, throughout the final iteration.

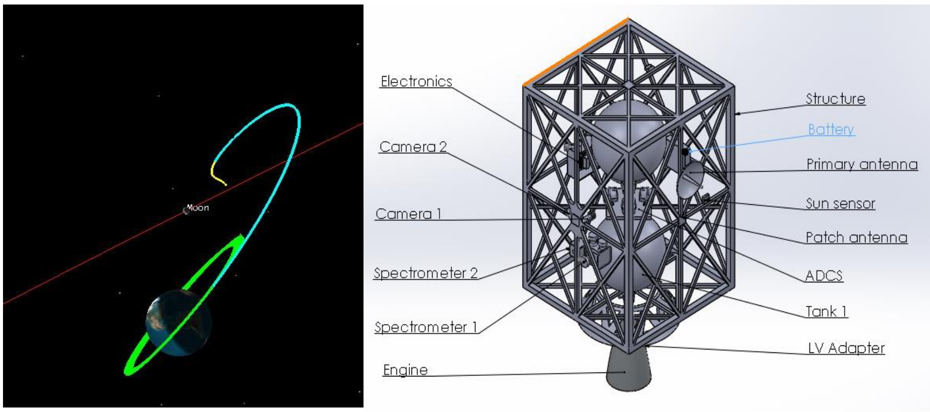

Figure 44 Wise Mission analysis (on the left) and System configuration (on the right)

Session 3,5-4: consolidate solution, knowledge transfer to CML5

During the last half session, the team focused its attention to the finalization and validation of the developed baseline solution. Analysis of gap filling activities and possible requirements validation approach have been carried out. Regarding the mission architecture, a reduced set of ground station within the EStrack constellation has been selected to guarantee continuous visibility of the satellite at least during crucial operations, and Ariane 5 was chosen as preferred launch vehicle. A single satellite with direct Earth-Moon transfer has been chosen as the preferred one even if the system was designed to perform a weak stability boundary transfer [75] as well. System architecture and equipment list were derived according to lunar harsh environment, e.g. micrometeoroids shielding, and mission worst-case scenarios. Thanks to developed virtual prototype, the team was able to validate the goodness of their results against mission constraints and stakeholder needs. Main drivers for follow-up iterations and concept maturity push have been identified with attention to the technology readiness level of the equipment list [76] (see appendix **E: Technology Reediness Level (TRL)** for further details). The equipment TRL was generally high (e.g. 8-9) for LEO orbit but a development/validation roadmap was foreseen to increase the confidence of these equipment list also in lunar orbit. Last, the disposal and system passivation strategy foreseen a controlled crash on the moon surface, nonetheless the team decided to further investigate the proposed solution. A final presentation and related documentation aimed to effectively transfer the knowledge among team members and with the other universities in a final video conferencing presentation session.

3.7 Final Thoughts and conclusion

This ESA academy initiative was very inspiring and a great chance to efficiently validate the developed methodology and tools. Students were enthusiastic about the participation in the challenge and in the follow-up concurrent engineering sessions. In this sense, Figure 45 shows the design team after that the certificates of participation have been delivered. Students successfully learnt how the CE approach is implemented and the many benefits it brings to the design. Even if most of them did not know each other, nor have worked together before, the team selection process and the team management approach introduced in 0 and 3.2.3 bring them to naturally become a team, very collaborative with each other. They carried out the tasks according to the input given by the systems engineers and considering “customer” needs. The developed Agile methodology with the support of Trello, sessions schedule and design tools encouraged the students, helping them to keep track of their tasks, assisting the learning experience while delivering good results in terms of study quality. This experience allows to state very confidently that the Agile CE approach can offer both students and experts a unique opportunity to learn about Space Missions Design and CE, enhancing learning, training and value delivery opportunities.

Figure 45 Students with their ESA academy certificate.

Chapter 4

Multi-stakeholder negotiation space exploration

In the previous Chapter, the application and tailoring of the concurrent engineering approach have been derived and analysed within an academic environment. This Chapter addresses the research question Q2 and those arising from it:

Q2: Can we improve, using quantitative methods, the level of quality and quantity of information aiming to obtain a "better faster and cheaper" space missions and systems design?

As it has been introduced in the Chapter 1, the evolution of space industry to the Space 4.0i era is pushing the space mission design process towards a multi-stakeholder environment. The increased interconnections among stakeholders increase the complexity of the design process, especially during early phases of the mission life-cycle. Performance, constraints and mission effectiveness are driven by stakeholder needs, which are in turn influenced by decisions taken throughout the system life-cycle. Once there is an interest to a system concept and a detailed design, consumer needs and resources limitation, including time and cost, usually prevent the design team from switching to alternative design solutions. Furthermore, the needs related to obtain more reliable missions, i.e. reduction of design failures, cost reduction and more effective complexity handling are equally important. To ease these issues, a new design methodology has been developed within this research. At this point, it is important to remark that the term *methodology* is often erroneously considered synonym of *process*. Within this research, the definitions provided by Martin et. al in [77] have been considered, and reported hereafter, in order to distinguish methodology from process, methods, and tools:

- A *Process* (P) is a logical sequence of tasks, aimed to fulfil an objective. A process defines "WHAT" has to be done, without specifying "HOW" each task is performed.
- A *Method* (M) involves a set of techniques to perform a task. It defines "HOW" each task can be carried out. At any level, process tasks are performed using methods.
- A *Tool* (T) is an instrument that, when applied to a method, can enhance the efficiency of the task, if applied properly and by a person with proper skills and training. The purpose of a tool should be to facilitate the accomplishment of the "HOWs.". Tools used to support systems engineering can be found in Computer Aided Engineering (CAE) tools.

With respect to these definitions, it is possible to define a *methodology* as a set of connected processes, methods, and tools. Roughly speaking, a methodology is a "recipe" of how exploiting related processes, methods, and tools to a class of problems that have some aspects in common. To have a broad view of a methodology development, it is also important to cite another definition related to the environment. An *Environment* (E) is built of external objects, conditions, or factors that impact on the actions of a system, a single person or a group [77]. Thus, it is important to consider capabilities and constraints given by technology, politics and economics, especially when shaping a system engineering development environment. Similarly, when choosing the proper mix of tools and methods, it is mandatory to consider the knowledge, skills and abilities of the people involved within the whole design methodology, taking into account special training and ad-hoc tasks to enhance related skills.

In order to improve the design performance, the so-called Multi-Attribute Tradespace Exploration (MATE) methodology [27] could represent a suitable choice. As already introduced in Chapter 3, the purpose of MATE is to capture decision maker references and use them to generate and evaluate a multitude of system architectures. The goal of MATE is to make trade-offs more explicit. However, when more than one party is involved in the decision-making process, the identification of a single design solution becomes more challenging, as the preferences of different stakeholders must be balanced and satisfied contemporary, even in the case of conflicting interests. Stakeholders generally aim for their own interests but, at the same time, they have to take into account the needs of the entire group and they have to face the impossibility of retreating from the design process.

The developed methodology, named *Multi stakehOlder NEgoTiation space exploration (MONET),* takes full advantage of concurrent engineering approach and modern tradespace exploration techniques, with the goal of enhancing the benefits provided by the approach itself, by speeding up and improving the effectiveness of space missions conceptual design. Exploiting the NASA JPL CML, the MONET methodology is built to rapidly evolve the maturity of the design from concept maturity level 1 (born of the idea) to level 7 (integrated preliminary baseline) while guaranteeing the project technical feasibility and the stakeholders' needs satisfaction.

This Chapter will follow a structured approach, according to the logic reported hereafter. First, a high-level overview of the methodology will be provided, presenting process, methods and tools exploited. Afterwards, a detailed description of the developed method and tools will be given for each task. On the other hand, for what concern methods and tools, first they are described theoretically, in order to understand the basics and possible application of the method within the design methodology. Then, a thorough description of the method application is introduced, with the intent to provide an user-friendly guideline on how to efficiently carry out the specific tasks and to finally apply the methodology to a case study.

4.1 Methodology introduction and high-level architecture

In this Section, a high-level overview of the proposed design methodology is given. In order to apply the methodology in an efficient and structured way, principal tasks, methods and tools are introduced and the main concepts behind the proposed methodology are analysed.

The process

The *goals* of the process within the design methodology are to speed up the design process, to increase the knowledge on the mission already in the conceptual design phase, to handle and to assist multi-stakeholder and negotiation problems while trying to guarantee a robust design solution with respect to uncertainties in the external environment. Moreover, the methodology aims at deriving more robust requirements, later in the mission development phases.

The concept of the whole process is captured in Figure 46. The main tasks involved within the process can be summarized as:

1. Elicitation of stakeholders needs, derivation of mission goals constraints and drivers; inclusion of decision making processes and uncertaties; derivation of mission high level requirements;
2. Set up and exploration of a “negotiation space”, taking into account external disturbances such as political and economical oscillacions which could efffect needs and preferences of involved stakeholders;
3. Identification of a negotiated conceptual design solution and evaluation of its robustness, in order to sucefully pass the first decision gate; derivation of system high-level requirments;
4. Study and analysis of the conceptual design at discipline level; locally exploration of discipline tradespace constrained by team decisions and evaluation of solution robustness in order to increase model trust and perception, as suggested by German et al. [78];
5. Revision, formalization and documention of selected preliminary design;
6. Derivation of robust requirments at mission, system, subsytem and programmatic levels.

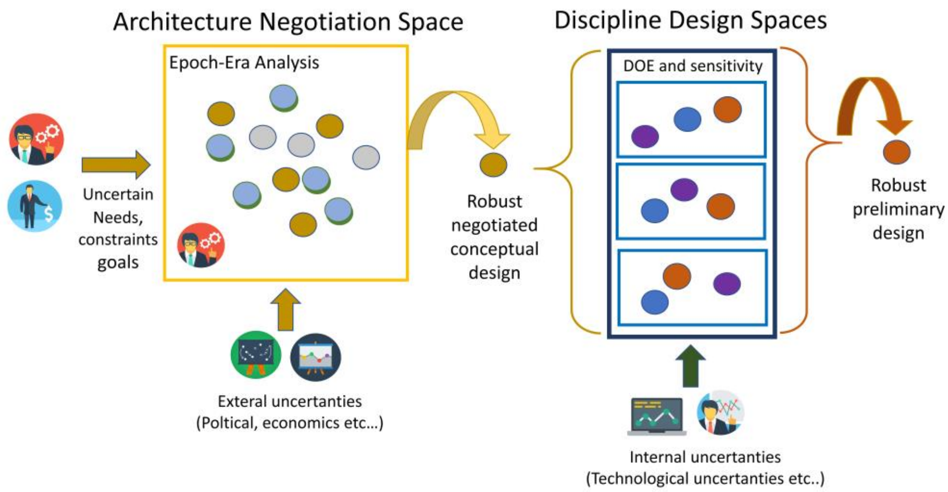

Figure 46 MONET Design process

Going into the details, in order to fulfill the aforementioned goals while avoiding any significant modification in the state-of-the-art process presented in Chapter 1, the detailed tasks involved in the process are displaced in Table

5. The MONET process encapsulates the concepts within the NASA JPL's CML presented in [60] and [79], trying to minimize the time spent for each CML push.

Table 5 MONET process

Id	Task	Objectives	CML target
T1	Stakeholder analysis (see section 4.3.1)	Understanding of stakeholder's prioritization, decision criteria and team decision style	1
T2	Stakeholder interview and engineering (see 4.3.2 and 4.3.3.4)	Elicitation of utility function, weights and collaboration constant	2
T3	Problem set-up (see 4.3.4)	Definition of MONET optimization architecture, design variables (local and global), mission context, high level mission constraints, definition of social accepted objective (s)	2
T4	MONET (see 4.3.4.5)	Definition of optimal design (s) with respect to both internal and external stakeholders	3
T5	Post optimality (see 4.3.4.7)	Perform Epoch-Era sensitivity analysis	4
T6	Design Assessment (see 4.4)	Finalization of negotiation process, finalization of design solution via Concurrent Design session	4 to 7

The methods

As introduced in the previous Section, the methodology is built-up over the methods summarized in Table 6, in which the target goal for each building block is highlighted. It is possible to observe that, while Table 5 summarizes the major tasks and objectives, Table 6 focuses on the methods infused within the process, as pictured in Figure 47, which tries to provide an overview of the whole developed design methodology.

Table 6 MONET Methodology: Methods and Tools

Method	Objective	Exploited in:
Multi Attribute Utility Theory	Modelling and exploiting stakeholder preferences	T1/T2
Expected Utility	Means of negotiation between negotiator and stakeholders	T3/T4
Game theory	Modelling and understanding the negotiation process among stakeholders	T3/T4
Collaborative optimization	Guide the negotiation process, efficiently searching for pareto equilibria among players	T4
Epoch Era Analysis	Evaluating the robustness of design solution with respect to uncertainties in external environment	T5
Artificial Intelligence	Assisting in uncertain decision-making phases via stored knowledge, automate recursive processes	T2,T6
Virtual Reality	Assisting decision making via visual analytics, increase trust and perception of design models and results	T6

The proposed methodology began with the stakeholder analysis. It must be underlined the great importance of this analysis within the MONET methodology. Indeed, since the architecture allows to implement different group decision styles, it results important to understand if, among the stakeholders, it is present a hierarchy or, in contrary, all the stakeholders have similar decisional power and interests, related to the mission under analysis. The following task consists in a structured interview, likely with a computer program avoiding external biases. This must be carried out in order to elicit stakeholder utilities, attributes and relative weights and the collaboration constants. The problem can be now settled-up, deriving the entity and boundaries of design variables related to each stakeholder.

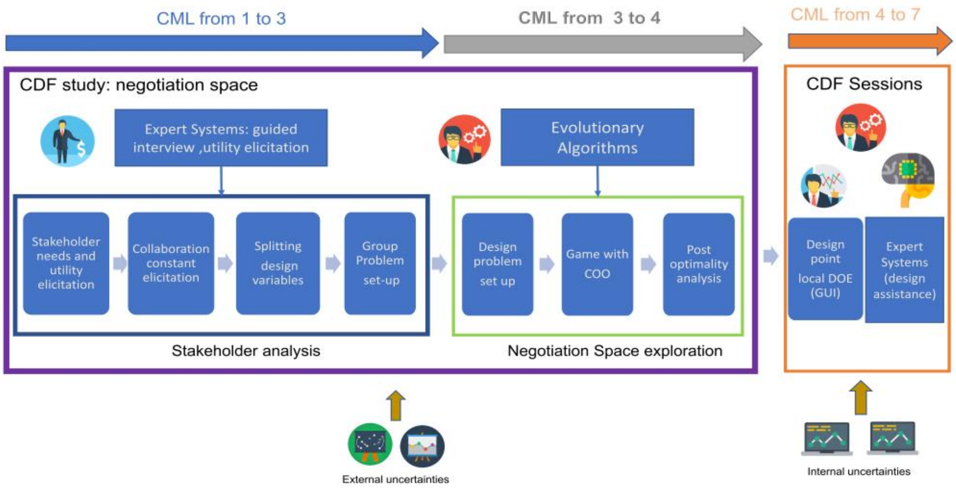

Figure 47 Infusion of methods and tools within MONET process

4.2 Artificial Intelligence for design assistance

Knowledge is 'The explicit functional associations between items of information and/or data'
Debenham, 1988

Before going into details of the MONET process, methods and developed tool, a theoretical introduction to a method, i.e. artificial intelligence, that has been exploited transversally throughout the process is hereby provided. This evolutionary algorithm has been adopted to answer the research question Q2.3:

Q2.3: How can we automate recursive processes, exploiting team knowledge, increasing the reliability of the solution design?

To properly answer this question, a brief analysis of what knowledge is and how can it be effectively exploited is recommended to avoid misunderstanding in the notation that has been used in this Thesis. Talking about knowledge and Artificial Intelligence in the same context, among all class of algorithms, the best choice to handle this kind of problems is represented by the so-called *knowledge-based* system algorithm. A knowledge-based system is a system, built around a knowledge base. i.e. a collection of knowledge,

taken from a human expert, and stored in such a way that the knowledge based system can reason with it [80], [81].
In this context, the word *knowledge* is intended as the sort of information that people use to solve problems and it can include facts, concepts, procedures, models, examples etc. Going into the details, a question arises easily: which are the main differences between data, information and knowledge? Within this research, the following definitions, suggested by Kendal et. Al. [81], have been adopted:

- *Data*: Individual measurement or design data, by themselves, are simply numbers, and therefore represent data.
- *Information*: Information can be identified as the context of the mission giving more details about the data. ***This information can be used by someone/something to make a decision***.
- *Knowledge*: Knowing the context and the nature of the mission allows to derive how to design the mission, how to use the design data and which decision should be taken during the system lifecycle.

Implicitly, moving from data to knowledge entails a shift from facts and figures to more abstract concepts, as pictured in Figure 48.

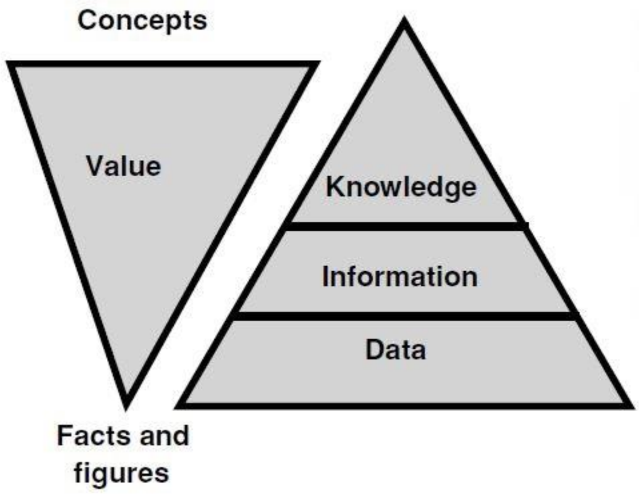

Figure 48 The pyramid of knowledge engineering [81]

In recent years, the approach to engineering has seen several evolutions, with important paradigm shifts on how design problems are solved, as highlighted in [82], [83]. One of the most interesting advances is the diffusion of Knowledge Based (KB) Engineering (E) and System (S), and, more in general, of the Knowledge Management (KM) methodologies. KM is a process that captures, develops, shares and uses effectively the organizational knowledge. It is spread in different domain of an organization and, if properly deployed, it allows to monitor and efficiently control the size and dispersion of an organization. Moreover, it helps reducing risks and uncertainties, improves the quality of the decisions taken, the customer relationships, *prevents knowledge losses, and organizes and plans the future use of knowledge*. KM is not a static methodology, and is both evolving in time, as more disciplines and domain embrace it, and evolves during the life of an organization, thanks to learning and adaptability features of the algorithms. The typical starting process of KM is the absence of any formal procedure of knowledge management. In time, the organization will develop processes that will be applied to more and more sections of its structure. Finally, the most advanced point in the evolution of KM is when an organization allocates resources and experts that take care of managing the business and knowledge assets.

The KM process results quite complex but it can be summarized by identifying the following four categories:

- Knowledge innovation;
- Knowledge documentation;
- Knowledge use;
- Knowledge sharing.

All of these aspects, from the activities regarding the identification and acquisition of knowledge, to its storage in databases, to the use and reuse, and to the diffusion among all the individual of an organization, are fundamental and must be applied correctly for the execution of the KM methodologies. Several elements of the KM process can be defined, and they are the subjects on which the KM process is applied to:

- People and skills;
- Procedures;
- Strategies and policies;
- Technology.

Lastly, for properly managing the knowledge in an organization, an appropriate set of resources must be allocated to implement or enforce the use of specific tools to help with this process, and they span throughout the four categories of the KM process. Among these, it is possible to identify for example meetings, simulations, presentations, product data management tools, knowledge trees, knowledge centres and so on.

A typical Knowledge-Based Engineering (KBE) system provides:

- A programming environment to code the experts' knowledge about the design of a mission, i.e. how the mission is defined, and the process of generating a mission by the systematic application of logical rules and various algorithms and procedures;
- A browsing interface to visualize the geometry of the mission and make queries about its geometric and non-geometric attributes, e.g. size, mass, cost, etc.

In the concurrent engineering process, the specialists are not permanently and exclusively assigned to CDF activities, as this is just one of the several tasks they perform in a matrix-organization. This specialist turnover implies that a large amount of knowledge can vary, in terms of good design practice and important knowledge from past missions, either successful or not. Concerning this flow of knowledge, it is important to avoid any loss of it, which implies the ability of managing and structuring the knowledge of each expert. This tool entails the introduction of a new role into the design team: the ***Knowledge Engineer***, whose tasks for each session shall be:

- *Knowledge acquisition:* obtaining knowledge from either experts (interview, etc..) or books.
- *Knowledge validation*: checking for adequate quality using test cases.
- *Knowledge representation:* producing a map of the knowledge and then encoding this knowledge into the knowledge base.
- *Inferencing*: forming links (or inferences) in the knowledge in the computer software so that the KBS can make a decision or provide advice to the user.
- *Explanation and justification*: exploiting additional computer program design, primarily to help the computer answer questions posed by the user and also to show how a conclusion was reached using knowledge in the knowledge base.

Once it is clear what knowledge, data and information mean within this context, the follow up question that could arise is: How can we represent knowledge? Knowledge representation is also of crucial importance in the field of Artificial Intelligence. The main component of a knowledge-based agent is its knowledge-base. A *knowledge-base* is a set of sentences, each of them being expressed in a language called the knowledge representation language. Sentences represent some assertions about the world. Logic is widely used in Artificial Intelligence as a representational method. The advantages of using formal propositional logic as a language of AI is that it is precise and definite and allows reason about negatives and disjunctions. Moreover, this representation of knowledge is easily human-understandable for debug or knowledge management tasks, as highlighted in [84].

In particular, this research focuses on the application of fuzzy rule-based systems, which also known as production systems or expert systems, and they represent one of the simplest forms of AI. A rule-based system uses rules as the knowledge representation for knowledge coded into the system [85]. The definition of rule-based system depends almost entirely on expert systems, which are system that mimic the reasoning of human expert in solving a knowledge intensive problem, as explained in [86]. Instead of representing knowledge in a declarative, static way as a set of things which are true, rule-based system represents knowledge in terms of a set of rules that dictates what to do or what to conclude in different situations. Any rule-based system consists of a few basic and simple elements reported hereafter:

1. *A set of facts*: These facts are actually assertions and they should be anything relevant to the initial state of the system.
2. *A set of rules*: It contains all actions that should be taken within the scope of a problem, specifying how to act on the assertion set. A rule relates the facts in the **IF** part to some actions in the **THEN** part. The system should contain only relevant rules and should avoid the irrelevant ones, because the number of rules in the system will affect its performance.
3. *A termination criterion*: It is a condition determining that a solution has been found or that none exists. It is necessary to terminate some rule-based systems that, otherwise, find themselves in infinite loops.

Facts can be seen as a collection of data and information, in which data associate the value of characteristics with a thing while conditions perform tests of the characteristics values in order to determine if something is of interest. In this sense, Figure 49 summarize the structure of a typical rule-based expert system, in which it is possible to notice functions and methods that have been previously introduced in this Section, such as inference, knowledge database, and so on.

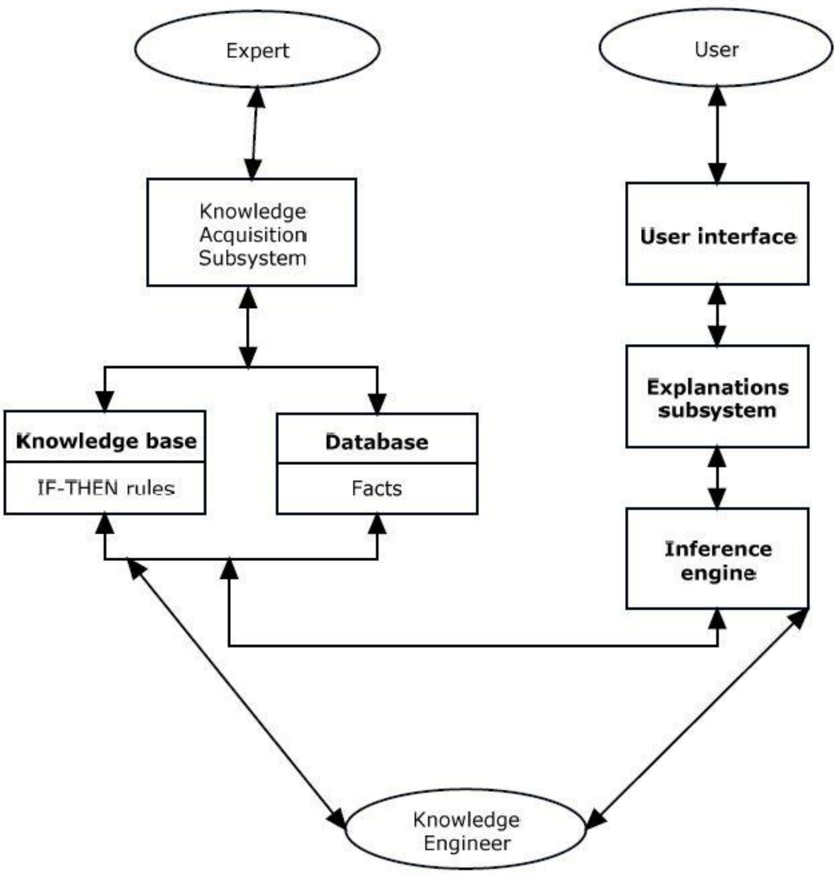

Figure 49 Structure of a rule-based expert system [87]

With the goal of properly modelling human knowledge and human decision-making process, it is necessary to introduce in the knowledge representation the concept of *uncertainties*. A detail description of uncertainties within the decision-making process will be given in the following Sections. In this Section, the attention will be focused on the modelling of uncertainties within knowledge representation. Uncertainty is essentially lack of information to formulate a decision. The presence of uncertainty may result in making poor or bad decisions. Dealing with uncertainty requires reasoning under uncertainty along with possessing a lot of common sense. When dealing with knowledge representation, especially in the design environment, there are several sources of uncertainty, as presented in [88] and listed below:

- *Imprecise language*: our (or expert's) natural language has to be transposed into IF-THEN rules. But sometimes our language is ambiguous and imprecise.

- Data (or information or knowledge) can be:
    - Incomplete;
    - Incorrect;
    - Missing;
    - Unreliable;
    - Imprecise.
- Uncertain terminology;
- Uncertain knowledge;
- *Incomplete information*: Information is not sufficient for the expert system to make a decision;
- *Imprecise data*: different terms are used with the same meaning or a term has multiple (different) meanings;
- *Combination of different expert views*: When huge expert systems require the presence of multiple experts, there is a low probability that all the experts will reach the same conclusion. They might have contradictory opinions, and this will involve the production of conflicting rules.

Thus, uncertainty may be induced by the degree of validity of facts, rule conditions and rules themselves. When dealing with uncertainty, we should be satisfied just with getting a good solution. There are several methods to pick the best solution considering uncertainty, among which: (i) probability-based methods, which include objective probability, experimental probability, subjective probability; and (ii) heuristic methods, which include certainty factors and fuzzy logic.

From the experience of medical application of expert systems, we decide to focus our attention on the modelling via certainty factors. This approach implies less data and r estimation to be carried out by experts.

Certainty theory is an attempt to formalise the heuristic approach to reasoning with uncertainty. Human experts weight the confidence in their conclusions and reasoning steps in term of "unlikely", "almost certain", "highly probable", "possible". These are not probabilities, but heuristics derived from experience.

A certainty factor is used to express how accurate, truthful, or reliable one judges a predicate to be. This judgment reflects how good the evidence is. A certainty factor is neither a probability nor a truth value. Certainty factors have been quantified using various systems, including linguistics ones (certain, fairly certain, likely, unlikely, highly unlikely, definitely not) and various numeric scales, such as 0-1, 0-10, and -1 to 1.

Certainty factors may apply to facts, rules (conclusion(s) of rules), both to facts and to rules.

When certainty factors apply to facts (evidences, premises) this represents the degree of belief (disbelief) associated to a given piece of evidence. A certainty factor value reflects confidence in given data, inferred data or hypothesis. The meaning of a certainty factor (CF) between -1 and 1 is:

- As the CF approaches 1 the evidence is stronger for a hypothesis.
- As the CF approaches -1 the confidence against the hypothesis gets stronger.
- A CF around 0 indicates that there is little evidence either for or against the hypothesis.

A more detailed analysis of CF can be seen in Figure 50.

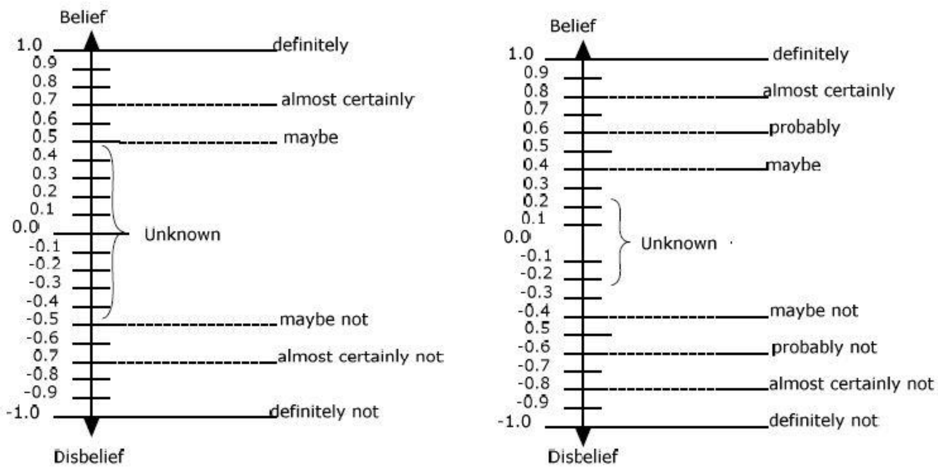

Figure 50 Uncertain terms and representations with certainty factor in expert systems [88]

What is reasoning? How can we exploit storage knowledge?

When talking about reasoning for rule based expert system is necessary to understand how it works.

A rule-based expert system works as follows: the inference engine compares each rule in the knowledge base with facts in the database. If the IF part of a rule matches a fact, then the THEN part is executed and the rule fires. By firing a rule, a new result (a new fact) may be obtained and this will be added to the database. By firing rules inference chains are obtained. An inference chain indicates how an expert system applies the rules to reach the conclusion or the goal. There are two main ways in which rules are executed and this conducts to the existence of two main rule systems:

- forward chaining systems. A forward chaining system starts with the initial facts and keep using the rules to draw new conclusions (or take certain actions) given those facts.
- backward chaining systems. A backward chaining system starts with some hypothesis (or goal) to prove and keep looking for rules that would allow concluding that hypothesis, by setting new subgoals to prove as the process advances.

Forward chaining systems are primarily data-driven, while backward chaining systems are goal-driven.

In the backward chaining we first state a hypothesis. Then, the inference engine tries to find evidence to prove it. If the evidence doesn't match, then we have to start over with a new hypothesis. If the evidence matches, then the correct hypothesis has been made. The backward chaining systems work backwards from a hypothesized goal, attempting to prove it by linking the goal to the initial facts. To backward chain from a goal in the working memory the inference engine must follow the steps:

1. Select rules with conclusions matching the goal.
2. Replace the goal by the rule's premises. These become sub-goals.
3. Work backwards until all sub-goals are known to be true. This can be achieved either facts or user provided the information.

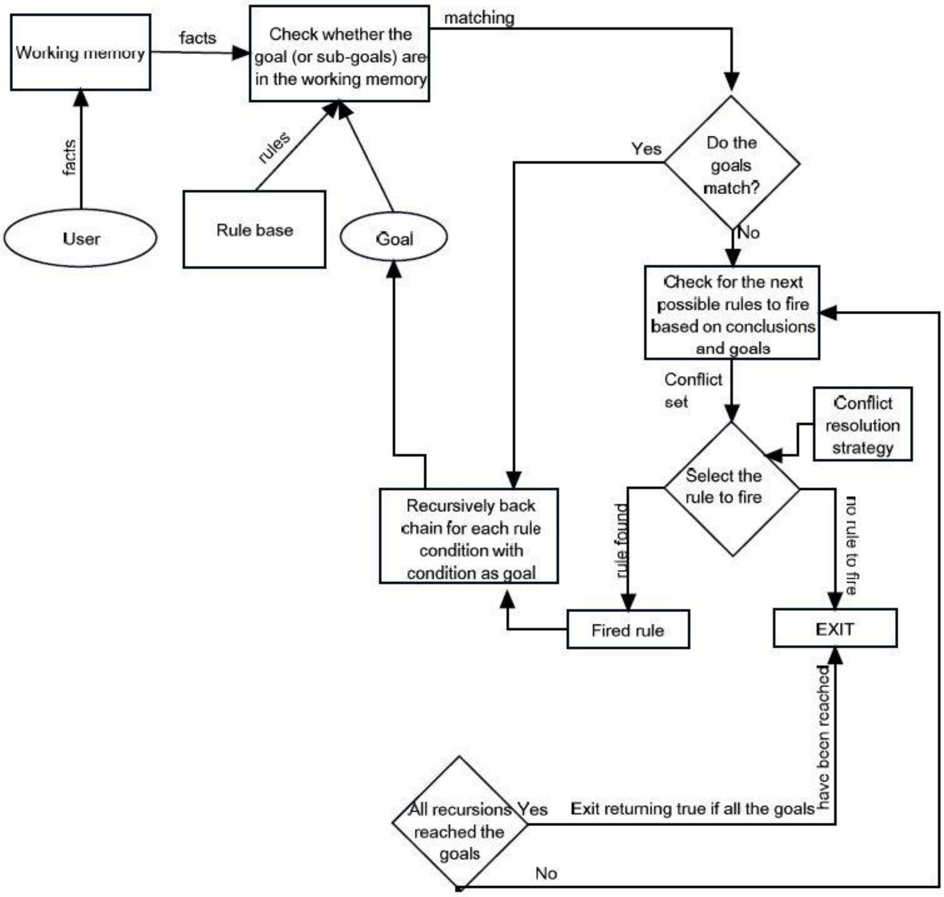

Figure 51 Backward chaining diagram [87]

When reasoning in an uncertain scenario, is possible to evaluate and to combine different certainty factor related to each rule depending on the logical relation between premises and conclusion of different rules (See Appendix F: Fuzzy reasoning: combining certainty factors).

A certainty threshold shall be identified to identify the limit from which a deduction is considered true or false statements and deductions.

In the context of knowledge acquisition and management a graphical user interface based Matworks Matlab has been developed.

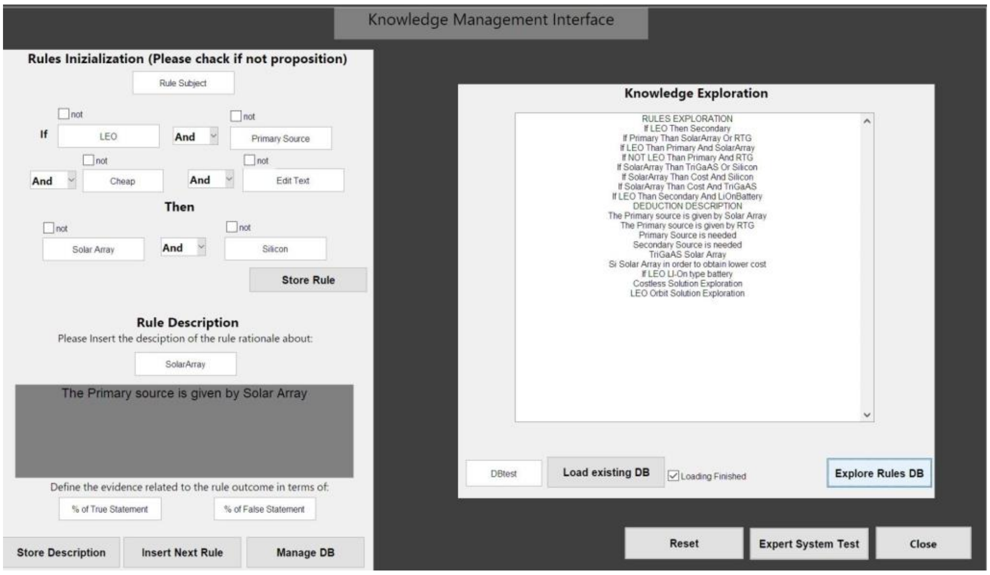

Figure 52 Rule Based Knowledge Management: Graphical User Interface

Figure 52 shows a nutshell of the developed graphical user interface. principal functionalities are related to the aspects and representation presented in this section. Propositional logic has been exploited to capture expert knowledge, moreover, a short suggestion of the context and description related to the nature of the rule must be given to obtain a suitable structure for knowledge management and transfer. Exploration of knowledge database and validation of the modelled knowledge is enabled by a tailored run of the developed Expert System within the context under analysis.

The developed knowledge management tool and the expert system will be introduced and exploited throughout several tasks in the MONET methodology, following the methods introduced in this section.

Pit Stop: Benefits of Expert Systems within knowledge management

Nonetheless the lack of creativity and invention which is intrinsic in AI algorithms, assistance to the design process giving by AI in the sense of Expert systems will represent an important step towards more reliable design with shorter schedule for the study process. Moreover, Expert systems;

- Process knowledge in the form of rules and use symbolic reasoning to solve problems
- Provide a clear separation of knowledge form its processing
- Trace reasoning in terms of fired rules in order to explain how a particular conclusion was reached and why specific data was needed (It is valuable also for teaching and training activities)
- Permit inexact reasoning and can deal with incomplete, uncertain and fuzzy data
- Enhance the quality of problem solving by adding new rules or adjusting old ones in the knowledge base. Changes are easy to accomplish.

4.3 The MONET methodology: Concurrent Engineering study

The first work package involved in the MONET methodology consists in the Concurrent Engineering study. This phase is principally aimed at system engineers and stakeholders, with the participation of the identified “most critical” disciplines. The goal of this phase is to push the maturity of the concept for the scratch idea (CML 1) to the selection of a reduced set of design options within the mission tradespace (CML 3, early CML 4). This set of option will be further analysed during the concurrent design session, presented in the next sessions. During this phase, the high-level requirements and the definition of mission architecture and concept of operations will be carried out in order to have a feedback from the involved stakeholders as real time as possible. With the aim of deriving robust requirements, the derivation of lower level requirements will be carried out after the selection of the design options. During this phase, in which the level of uncertainties is the highest, the derivation and exploration of the negotiation space and the follow up negotiation analysis is performed.

In this Section each subsection is structured as follows: (i) theoretical introduction to the exploited method; (ii) adaptation and tailoring to the MONET methodology; and (iii) application to case study(ies).

Presentation of the case study and mission understanding

According to the ESA exploration strategy presented in [89] and the Global Exploration Roadmap [90], the Moon will be the next destination for humans venturing beyond Low Earth Orbit and it will represent an integral element of the path towards human missions to Mars. The Lunar Exploration Vision 2030 requires new approaches and innovative ideas to be included in the step-wise deployment of the international exploration architecture. A guiding principle is to implement coordinated human and robotic missions enabled by broad international cooperation. Small spacecraft missions are expected to play an important role to support the global Moon exploration objectives, as they can address key scientific and technology areas timely and at low cost compared to flagship missions. They are also suitable means to demonstrate, in a relevant environment, technologies and approaches that might be useful for larger future exploration missions. In recent years, several small satellite missions have demonstrated their ability to pursue a broad set of mission goals, including science, technology demonstration, communications, and Earth observation, with a significant cost reduction and a relatively faster development time, from design to operations, compared with traditional larger-satellite missions. CubeSats allow building brand new architectures, which would be unattainable with bigger satellites. Constellations of nanosatellites in LEO, and lunar and interplanetary CubeSat missions are becoming a reality, as highlighted in [45], [91]–[94].

Within this framework, the study under analysis will address the challenge of *deploying & operating a CubeSat-based space asset in the vicinity of the Moon, to complement and add value to ESA's lunar exploration objectives, providing unprecedented measurements and data about the Moon targeted to science and knowledge-gap-filling activities for space exploration, and to the demonstration of supporting key technologies development.*

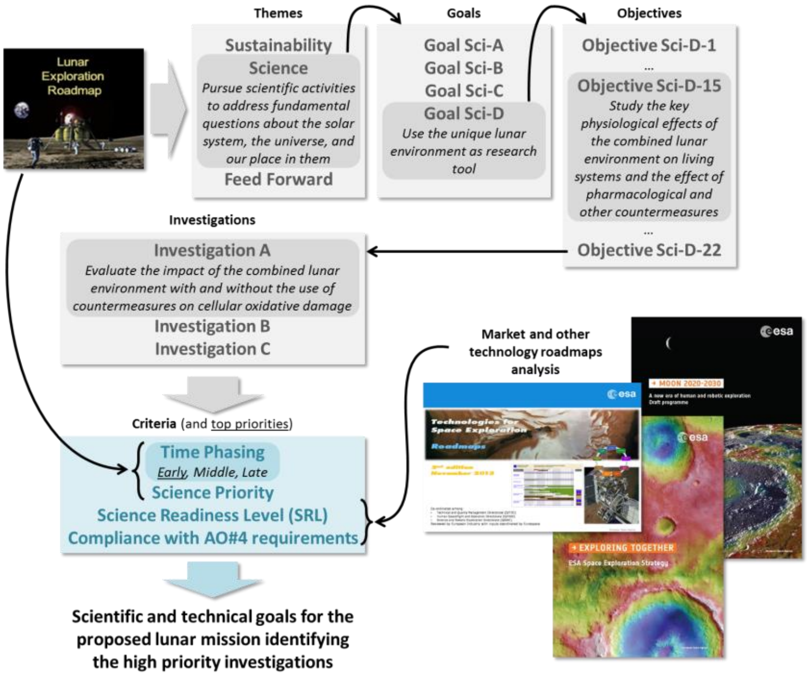

Figure 53: Process leading to the identification of the scientific and technical goals for the proposed lunar mission

A logical process can be put in place, aimed at identifying and justifying the goal(s) and objectives for a lunar CubeSat mission. A thorough analysis of the lunar exploration roadmap [20] led to the identification of which investigations, needed to fill the knowledge gaps in a specific domain, are relevant within the present study and better address the challenges and opportunities of a CubeSat-based mission to the Moon. Through the process depicted in Figure 53, it is possible to identify a group of high-priority investigations able to fulfil specific gaps and needs for enhancing space exploration. The full range of investigations, proposed by the Lunar Exploration Analysis Group (LEAG) and summarized in [74], is considered and ranked according to the following criteria:

- Time phasing (Early, Middle, Late) [74];
- Science priority (High, Medium, Low) [74];
- Science readiness level (SRL 1 to SRL 9) [95].

Given the nature of the CubeSat mission, it seems preferable to focus on those investigations having high-science priority and early-time phasing.

Considering the two themes that can solve the higher number of investigations related to Moon Exploration, high-ranked investigations are in the area of lunar radiation environment characterisation. Among these, specific investigations are needed to understand the physiological and biological effects of the lunar environment on non-human life forms. Furthermore, a high-degree of on-board autonomy will help to achieve the goal of reducing operations costs of small satellite interplanetary missions. Increasing the degree of mission autonomy might help overcoming the limitations imposed by the typical low data rate and the issues related to the ground support for CubeSat missions. In conclusion, the following science and technology goals with associated objectives have been identified for the mission under analysis:

- *Science Goal*: To understand the unique lunar radiation environment and its dependency on solar activity and seasonal variation.
  - Objective: To characterise the radiation environment in the vicinity of the Moon with unprecedented spatial and temporal resolution.
- *Science Goal*: To understand how the lunar radiation environment affect the proliferation of specific organism.
  - Objective: To study the survival and active metabolism in the extreme lunar radiation environment.
- *Technology Goal*: To develop novel technologies and operational approaches for CubeSat missions beyond LEO.
  - Objective: To validate innovative on-board autonomy approaches based on AI technology.

The customer gave also a set of drivers and constraints. Thus, the study has been driven by the following guidelines:

- One or multiple small spacecraft shall be inserted into a proper lunar orbit by a larger Lunar Orbiter providing transportation and data relay services.
- During nominal operations, the small spacecraft shall make use of data-relay services, provided by the Lunar Orbiter to Earth, from a highly elliptical polar orbit characterised by:
  - Periselene altitude: 800 km;
  - Aposelene altitude: 8000 km;
  - Inclination: near-polar.
- Avoiding plane change: assume that the orbiter deploys the small-satellite(s) in the operative orbit plane.

- Single spacecraft mass up to 24 kg.
- Total mission mass up to 60 kg.
- Ensuring orbit stability in order to obtain biological repeatability and to reduce propellant mass for orbit maintenance.

The following sections will go through the application of the MONET methodology, following the introduced process and underlining both theoretical and practical methods. In particular, the first task is referred to the stakeholder analysis.

4.3.1 Stakeholder analysis

The primary focus of any system engineering effort is on the stakeholders of the system, the definitions of which have a long chronology in the management sciences literature, as presented in [96]. Projects have a variety of stakeholders and, during the project planning phase, which is prior to implementation, it is imperative that a stakeholder analysis is carried out. The main goal is the identification of the project stakeholders and their potential impact on the project, even in the smallest ones. Getting stakeholders collaborative and maintaining them both updated and satisfied is demanding to the success of the project and the project manager needs to put considerable effort to managing stakeholders effectively. The output of the stakeholder analysis provides with information about which category stakeholders belongs to, among primary, secondary, tertiary and key stakeholders. Primary stakeholders are those who will be most affected by the project. Secondary stakeholders are those who are less affected by and in the project. Tertiary stakeholders are those for whom a minimum impact in foreseen. The most important stakeholders, however, are the primary stakeholders, as they can significantly influence the success of the project and/or are very important to the project. This will grant that all the decisions taken during a project and all the following activities will be focused on satisfying their needs.

As the stakeholders include all the institutions and people that request and support the mission development, it is important that the final product, i.e. the mission, is tailored to their intentions and ideas. The drawback of this is that the needs are not always clearly identified. A whole methodology has been developed in order to provide the mission planners with analysis and reports that clearly define the stakeholders' needs, starting from obscure and undefined ideas (not always the stakeholders are technical people). Thus, the rationale for developing a good and as complete as possible stakeholder analysis can be summarized as:

- Assess how stakeholders could be impacted or impact upon the organisation.
- Anticipate the consequences of any change in the organisation's activities.
- Identify stakeholders' success criteria and possible risks.
- Assure a successful outcome for the organisation by developing cooperation with stakeholders.
- Derive robust (in time) and value-driven mission objectives, constraints and requirements.

Stakeholders' involvement is critical to the success of the systems decision process. Stakeholders ensure that there is the right context for taking decisions, helping the system engineer to have reliable and direct information. Their early involvement is essential for their commitment to action necessary to implement the decision. Indeed, without stakeholders' involvement, decisions will not be sustainable, and stakeholders may force costly decision changes. Stakeholders have important roles in each phase of the systems decision process. Sooner or later, for any systems decision problem, stakeholders will care about the decision reached because it will affect in one way or another the stakeholders themselves, their systems, or their success. Consequently, it is prudent and wise to identify and prioritize stakeholders in some organized fashion and to integrate their needs, wants, and desires in any possible candidate solution.

4.3.1.1 Stakeholder identification

In the context of system engineering, a stakeholder is a person or organization that has a vested interest in a system or its outputs. When such a system is an organization, this definition aligns with Freeman's on as stated in [97]: "*any group of individuals who can affect or is affected by the achievement of the organization's objectives*". It is this vested interest that establishes stakeholder's importance within any systems decision process. Taking into account ECSS-recommended terminology as reported in [73], but with the addition of Wertz et. al. proposed one as in [98]. The principal actors to be considered at an initial stakeholders' screening shall be the following:

- The *sponsor*, the entity who pays for the system and establishes the constraints, cost ceiling, desired schedule, programmatic framework, and any set of appropriate guidelines, to be applied to the implementation of the space system.

- The *consumer*, the community who uses the output of the system and who establishes requirements on the quantity, quality, and mode of delivery of the data to be produced by the space system.
- The *customer*, the entity who represents the interest of the consumer with respect to the supplier, who specifies the system, oversees its implementation, accepts and certifies it, delivers the system to the consumer, and is responsible to the sponsor for finishing on time and within the cost ceiling.
- The *supplier*, the entity who interacts with the customer, helps in the preliminary design, performs subsequent detailed definition and development, builds the system, delivers it to the customer, and is paid by him.

With the goal of performing a better stakeholders analysis, a good practice is given by setting up a *team brainstorming session,* driven by the following questions:

- Who is paying for the system?
- Who is going to use the system?
- Who is going to judge the fitness of the system for use?
- Which agencies (government) and entities (non-government) regulate any aspect of the system?
- Which laws govern the construction, deployment, and operation of the system?
- Who is involved in any aspect of the specification, design, construction, testing, maintenance and retirement of the system?
- Who will be negatively affected if the system is built?
- Who have we left out?

During these brainstorming sessions, it is important to extend the view of possible stakeholders. This means that is important to not consider the mission developing process like a closed system, but instead, try to analyze both internal and external environment. In this case, the external environment of the mission life cycle is subdivided in:

- Technological;
- Economics;
- Political;
- Health and Safety;
- Social;
- Cultural;
- Ethical.

4.3.1.2 Stakeholder prioritization and management

Managing stakeholder needs is mandatory to project success. Several methods have been developed to analyse the interrelationship among key individuals and the challenges that could arise as a project begins. Mitchell et al. posit in [6] that stakeholders can be identified by their having one, two, or all three of the following attributes, which have been generalized here to systems.

1. The stakeholder's power to influence the system.
2. The legitimacy of the stakeholder's relationship to the system.
3. The urgency of the stakeholder's claim on the system.

A good stakeholder analysis provides the project manager with information about the interests and needs (and any conflicting interest) of stakeholders. It will also help stakeholders understand more about the project. Ultimately, it will help the project manager and system engineers to identify project risks and to provide a basis for negotiation set-up. Table 7 gives an outlook on typical stakeholder prioritization and management based on his/her interest and power in the project.

Table 7 Interest/power grid for a project stakeholder

High/Low Decisional Power	**Low interest**	**High Interest**
High power	Defenders to Keep satisfied	Promoters to Manage Closely
Low Power	Apathetic to Monitor	Latent to Keep informed

4.3.1.3 The Apollo program: benefits of stakeholder analysis

In this Section, a short case study of stakeholder analysis is presented, highlighting the importance and the impact that a well-done stakeholder analysis might have to a whole programme. The selected case study is set in the Apollo era, with the birth of the today's NASA program management. In 1961, John F. Kennedy in his well-known speech at Duke University stated the top-level needs and requirements of the Apollo program as reported in [99]:

- Put an US astronaut on the Moon;
- Return him safely;
- Accomplish the mission by the end of the decade.

It is possible to explore the actual stakeholders and related needs involved in the Apollo program as listed in the follows:

- J. F. Kennedy: Political power and reputation;
- US congress: Funding a decadal undertaking;
- NASA: Organizing the implementation;
- Universities: Exploring the novelty, be involved;
- Industry: Develop and implement, costs;
- General public: Curiosity, identification, be involved;
- Astronauts: Be safe, Be on the Moon;
- Mission Operators: Be able to bring the man on the Moon.

Each stakeholder involved in the project has differing perspectives on how to go about the task of accomplishing Apollo. A way to manage all the stakeholders and their needs should be found in order to properly fulfil the goals expressed by Kennedy. NASA expanded the "program management" concept borrowed by T. Keith Glennan in the late 1950s from the military/ industrial complex, bringing in military managers to oversee Apollo [100]. A programmed office was created with centralized authority over the following areas: Design, Engineering, Procurement, Testing, Construction, Manufacturing, Spare parts, Logistic, Training and Operations. There was a large amount of data and material collected as the result of the lunar missions. For example, during each mission, the crew emplaced and activated a lunar geophysical observatory to be controlled and monitored from Earth, collected samples of lunar soil and rock, photographically documented the geologic features of the landing area, and performed other exploration activities.

The Apollo project (mission 8) allowed the world to view the whole Earth for the first time in the history of mankind. The operational and scientific success of that missions stimulated a vigorous interest in the Solar System and established the study of the Moon as a modern interdisciplinary science. There was an impressive range of results from the scientific experiments related to lunar orbital science and lunar orbital science. The mission reports for 11 manned missions showed a continual improvement in flight crew performance[99]. The increased complexity in the objectives of each mission was possible because new operational experience was used, where appropriate, to standardise and revise crew operations as each mission was flown, especially in the areas of pre-flight training, flight procedures and equipment operation. The overall success of the Apollo era would not be the same without a proper identification and management of the involved stakeholder, proving the importance of these tasks within every engineering project.

4.3.1.4 Case study

Hereafter, the development of the first task within the MONET process, i.e. the detailed stakeholder analysis, is presented. Following the concepts presented in the theory building Section, after the presentation of the mission context and high-level constraints, a brainstorming session has been carried out in order to identify all the entities involved in the mission development process. The results of the stakeholder identification and management is pictured in Figure 54. In this sense, the political community and the customer has ben identified as promoters, which must be manage closely, trying to balance and satisfying their needs since they possess a higher decisional power. The standards imposed by the "regulators" through the ECSS must be satisfied but they don't truly have a deep interest in the success mission itself. Internal stakeholders, such as designers and architects, have also been considered to properly set up a development roadmap, according to their balanced needs. Last but not least, social community or general public has been taken into account in order to foster space related activities, involving general public imagination and curiosity.

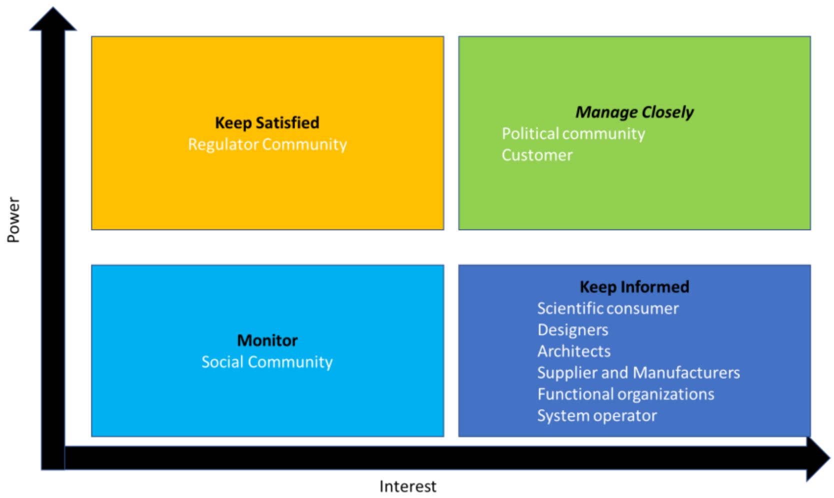

Figure 54 Case study: stakeholder identification and management

4.3.2 Needs elicitation and decision-making process

"*Not everything that can be counted counts and not everything that counts can be counted.*"

-Albert Einstein

Once the stakeholders have been identified, the next process in the MONET methodology involves the elicitation of their needs. Before starting the generation of idea and alternatives, it is important to have a clear definition of "what is the real problem to solve". This question is answered and solved via the stakeholder needs analysis and identification. With the goal of understanding how this process is done within the MONET methodology, an introduction to elicitation methods and to advanced decision-making techniques is hereby provided. The follow-up task regards needs identification and their translation in mission attributes. This process has been done in order to clearly understand stakeholders needs, design constraints and design drivers. Furthermore, for a scientific stakeholder analysis and for traceability porpoise, a Science traceability matrix (STM) has been developed (see appendix G.1: Lunar CubeSat case study: Science Traceability Matrix) following the approach proposed in [101]. which gives a clear traceability on how the science objectives are translated into mission and payload requirements, enabling to understand scientific needs and translating them into mission requirements, and ensures traceability of mission requirements exploiting structured approach.

4.3.2.1 Interviews

Interviews are one of the best techniques for the stakeholder analysis, if one wants to obtain information from each individual separately. Interviews are especially appropriate for senior leaders, who do not have the time to attend a longer focus group session or the interest in completing a survey. However, interviews are time-consuming for the interviewer due to the preparation, execution, and analysis time. Since interviews take time, it is important to get the best information possible. The following are best practices for each phase of the interview process: planning, scheduling, conducting, documenting, and analysing interviews. For interviews with senior leaders and key stakeholder representatives, it is important to prepare a questionnaire to guide the interview discussion. It is usually not a best practice to provide detailed questions ahead of the interview for two reasons. First, the purpose of the interview is to obtain information directly from the stakeholder and not from a representative. If the interview questions are provided in a read-ahead packet, there is a likelihood that the stakeholder's staff will prepare responses to the questions, thereby defeating the purpose of the interview. Second, the systems team conducting the interview should have the flexibility to add questions and/or follow-up on valuable information leads should they arise. If the stakeholder is preconditioned by knowing the interview points in advance, the team might not be able to adapt the interview during the interview. The interview team creates an important first impression with the senior leader about the team that will develop a solution to the problem. The goal of the interview is to obtain the stakeholder insights in a way that is interesting to the interviewee. As the outcomes are identified, it is important to not focusing on potential findings that are interesting but unrelated to actual stakeholder analysis. If appropriate, these findings should be presented separately to the decision makers.

4.3.2.2 Focus group

Focus groups are another technique for stakeholder analysis, and they are often used for product market research. However, they can also be useful for determining relatively quickly how groups of stakeholders feel about a specific systems decision problem. While interviews typically generate a one-way flow of information, focus groups create information through a discussion among group members, who typically have a common background related to the problem being studied. Typically, focus groups are composed by 6–12 individuals. Too few members may lead to a too narrow perspective, while too many may lead to some individuals not be able to provide meaningful input. As with interviews, the focus group team needs to allocate time to the preparation, execution, and analysis of data gained from focus groups. Analyzing the information, focus groups can provide a great source of qualitative data for the systems analysis team to analyze and create useful information. First, the recorders should verify the raw data that was generated during the session. Then, these data should be processed into findings, conclusions, and recommendations, using the methods discussed in the interview section of this Chapter

4.3.2.3 Surveys

Surveys are an effective methods for gathering information from large groups of stakeholders, especially when they are located in different locations. Surveys are appropriate for junior to mid-level stakeholders. If the problem is of interest, surveys can be used to gather quantitative data that can be analyzed statistically, in order to support conclusions and recommendations. Systems engineers can share and gain survey data via mail, electronic mail. As with any stakeholder analysis technique, surveys require detailed planning to accomplish its goals. The stakeholder analysis team needs to clearly articulate the goals of the survey and the target sample of stakeholders, whom they want to answer the survey. Often, surveys for systems engineering decision problems will be used to collect textual answers to a standard set of questions. Popular methods for survey execution are mail, electronic mail, and web surveys. The ability to collect survey responses in a database when using a web survey instrument can be extremely beneficial to the stakeholder analysis process. Nowadays, there exists several online programs to help teams to design web surveys, collect responses, and analyze the results such as Goggle Forms. A key part of the analysis effort will be in formatting the survey data that are received. If a web survey is used, the team can program the survey instrument to put responses directly into a database file. This allows the team to perform statistical analysis on objective-type questions relatively quickly. The goals of the analysis are the same as for interviews and focus group sessions. Similar to the process discussed earlier in this Section, the team should bin the responses by survey questions and analyze these responses to develop findings.

Table 8 Stakholder survey methods[66]

Survey Method	Advantages	Disadvantages
Mail	• Respondents have flexibility in completing the survey	• Time consuming • Hard to check compliance • Response data will have to be translated for analysis
Electronic Mail	• Fast to distribute and get responses • Low cost • Easy to check compliance	• Need to obtain e-mail addresses • Response data will have to be translated for analysis
Internet Web Survey	• Extremely fast • Can include special graphics and formatting • Can collect responses in a database to facilitate analysis	• Respondents can give only a partial response to the survey

4.3.2.4 Stakeholder interview Techniques: summary

The following Section summarizes the major characteristics of each stakeholder analysis method that has been introduced in this Chapter. In particular, ideal group of stakeholders, preparation and execution phases and results analysis are hereby summed up.

Table 9 Stakeholder interview methods a summary

	Average time	**Ideal stake-holder group**	**Prepara-tion**	**Execu-tion**	**Analysis**
Inter-views	30-60 minutes	Senior project manager and key stake-holder	Develop interview question-naire(s) and sched-ule inter-views.	Struc-tured conversa-tion with senior leader us-ing ques-tionnaire as a guide. Separate note should be taken.	Interviewer reviews typed notes. Analyse to determine findings, conclusions, and recom-mendations.
Focus group	Shortest: 60 min typ-ical 4-8 hours	Mid-level to stake-holder represent-atives	Develop meeting plan, ob-tain facil-ity, plan for record-ing inputs.	At least one facil-itator and one re-corder.	Documenta-tion of ob-servations. Analyse to determine findings, conclusions, and recom-mendations.
Sur-veys	5-20 minutes	Junior to mid-level stakehold-ers	Develop survey questions, identify survey software, develop analysis plan.	Complete survey question-naire, so-licit sur-veys, and monitor-ing com-pletion status	Conclusions must be de-veloped from the data.

4.3.2.5 Introduction to Prospect theory, biases, farming and risk attitude

A rational decision requires a clear goal, a scenario with perfect information and an optimal strategy (or course of actions) in order to maximize expected value of the decision outcomes. Decision Makers (DM) knows all the options available and the consequences of each one. Prospect theory gives an overview of the possible decision scenarios that can be faced by a decision maker. Innate human biases, external circumstance, can bring to misleading decisions. To avoid misunderstanding with the word "risk", in the decision theory is preferred to split the concept of risk in ambiguity, uncertainty and hazards. This split is also supported by the fact that decision that involves one of each single concept is made in different parts of the brain.
Within this scenario, humans prefer the alternative with the lower variance, i.e. lower uncertainty, and try to avoid ambiguous decisions.

Pit Stop:

The most important principle of human fallibility with decision making is the confirmation bias: humans hear what they want to hear and reject what they do not want to hear.

Thus, human beings usually exclude information that deny their preconceived notions and force things that booster their beliefs. This causes decision makers to actively seek out and assign more weight to evidence that confirms their hypothesis and ignore or under-weigh evidence that could disconfirm their hypotheses. Last but not least, the decision makers are most affected by framing (context of a question) and severity amplifiers. Framing means embedding observed events into context that gives them meaning. Context gives consistency to experiences, avoiding random and unrelated ideas. The stakeholder has a vision, mission, values, morals, ethics, beliefs, evaluation criteria, and standards for how people think and how people should behave. Collectively, these are called *principles.* They are basics of strategies, goal and thus decisions. Each goal entails a plan to reach it and each plan has two main aspects:

- *Tactics*, which are the concrete behavioral aspects that deal with local environments;
- *Forecast*, which is the animation of the future that provide scenario for forecasting what might result if the tactics are successful.

The decision maker exploits contextual information to trigger his or her memory. Recognition of context for similarity, defines which principals, goal, plans are relevant to the current context and provides information about goals and plans that were previously pursued in this context. If similar goal is being pursued, then the plan that was used before may be used again.

The utility of the outcomes of decisions derives from the degree to which these decisions conform to and enhance the decision maker principles. Framing also influences the so-called *severity amplifiers,* such as lack of control, lack of choice, lack of trust, lack of warning, luck of understanding, manmade, personalization, ego, uncertainty, immediacy. It is immediate to understand how these severity amplifiers can modify the outcome of a decision.

Pit Stop:
The secret of a successful balance between rational and human decision is creating a frame of reference with just the right amount of details.

4.3.2.6 Introduction to descriptive theory and subjective decision making

The consequence of context dependence means that the objective value is not considered in an absolute sense, i.e. from zero, but it is subjectively established by the subject perspective within the preliminary screening phase.

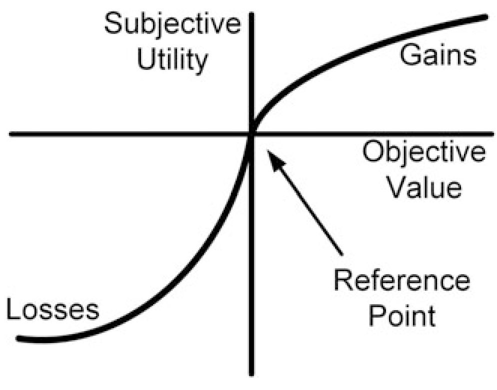

Figure 55 Objective value to Subjective Utility[102]

Form Figure 55, it is possible to underline that:

- Gains are valued about half as much as losses;
- Gains and losses are relative to a reference point;
- Gains and losses present saturation.

This proven fact of human decision-making highlights that, even in the presence of required knowledge and resources, people tend to not make rational decisions because they do not evaluate utility rationally. Indeed, most people would be more concerned with large potential loss then with large potential gain.

Pit Stop
Losses are felt more strongly than comparable gain, since people prefer to avoid losses more than they prefer to get gains**.**

Subjectively, small probabilities are overestimated whereas large probabilities are underestimated. Figure 56 shows the typical trend in the human probability estimation. People tend to overestimate the probabilities of low-likelihood events and underestimate the probabilities of high-likelihood events.

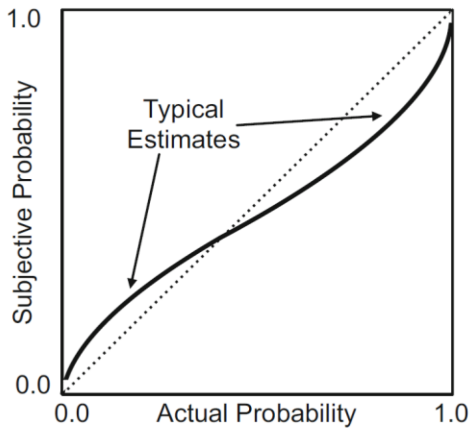

Figure 56 Subjective Probability: Typical Human Estimation.

4.3.2.7 Context dependence and Monty Hall paradox

People shows context-dependence: an alternative A is chosen more often than an alternative B due to the presence of an irrelevant third alternative C.

Pit Stop
Context-dependence means people compare choices within a set rather than assigning separate utility.

The context dependence is also exasperated by the fact that humans are not good at estimating probabilities as demonstrate by the Monty Hall paradox[103]. Due to status-quo bias, most of the people prefer to stick with what they have.

4.3.2.8 Subjective expected utility

Subjective Expected Utility is the product of two subjective concepts: utility (or subjective value) and subjective probability (frequency or the likelihood of an event to occur). The descriptive model of human decision-making claims that humans are biased to maximizing subjective expected utility, as:

- *Maximized* because people choose the set of alternatives with the highest total utility;
- *Subjective* because the choice depends on the decision maker's values and preferences and not on reality;
- *Expected* because expected value is used.

Pit Stop
Humans are biased to maximize subjective expected utility.

In most cases, the utility functions are non-linear due to the non-linear evaluation of subjective benefit. Figure 56 shows the typical behavior of subjective utility with respect to un-increasing of benefit that they might receive.

Pit Stop
The utility functions are in most of the cases non-linear due to the non-linear evaluation of subjective benefit that they might receive. When you are hungry, you will place a high utility on your first plate of food and then, the need of food decreases, the utility of each sequent plate decreases till a saturation occur. You are full.

As it has been introduced in the previous Section, in this scenario the subject of the analysis attached less and less utility to each addition of a unit of benefit until the saturation is reached. The subjective utility is also strongly correlated with the concept of uncertainties and ambiguity (or risk) involved in the unknown outcomes of a decision. Utility function can picture the so called "*risk behave*" of the people. For instance, the diminishing utility and risk aversion are strongly correlated.

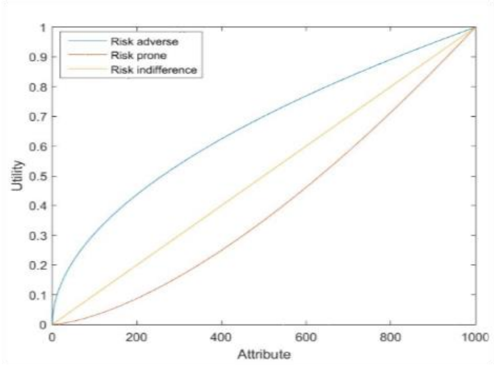

Figure 57 Utility function and risk behave

In Figure 57, it is possible to see the three major people behaves and the corresponding utility shapes, where the set-point of the benefit is set to zero. The main characteristic that underline the behave is the concavity of the utility function. In particular, it is possible to notice that for:

- *Risk aversion*, the preferred choices are the one with less reward but more profitable (or certain), or the mean of the subjective utility relies underneath the mean of the benefit (or attribute) interval. The concavity is negative.
- *Risk prone,* the preferred choices are the one with more reward but less profitable (or certain), or the mean of the subjective utility relies beyond the mean of the benefit (or attribute) interval. The concavity is positive.
- *Risk indifference* (utopia scenario), the mean of the subjective utility corresponds to the mean of the benefit (or attribute) interval. The concavity is zero.

Once that the subjective utility concepts have been introduced, the next issue involves the following question: is it possible to effective measure the subjective utility? The concepts of subjective expected utility and framing can help with the measure of the utility itself. Recalling that the subjective expected utility ($U_{expected}$) in a uncertain scenario is equal to subjective probability (P_i) times subjective utility ($U(X_i)$), referred to a benefit (or attribute) X_i [104], it is possible to write the following equality

$$U_{expected} = P_i U(X_i). \tag{1}$$

The methods for determining subjective utility have a common characteristic: they establish an equivalence between stimulus and response. The stimulus is provided in the measuring process, to provoke a person's response, indicating the preference, i.e. the utility. The process is analogous to radar identification of an object: a signal goes out and the response interprets.

Pit Stop

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The stimulus is built with an ad-hoc use of framing and uncertain scenarios, i.e. a binary lottery of the form

$$(X_1, P; X_2) \tag{2}$$

where the variables X_i are the proposed outcomes of a decision with probability P and P -1 in a determinate context. The key factor is that the stimulus contains no more than one X_i, which utility is unknown. In particular, it is possible to summarize the concept of utility elicitation as

Utility of response (with one unknown utility X_i) = Utility of stimulus (of known utility)

The sequence of observations can be obtained by varying the probability of the outcome while keeping the outcome constant. This approach is called *lottery equivalent probability*. The lottery equivalent approach uses binary lottery to simulate the stakeholder and evaluate his subjective expected utility. After the preliminary screening, the possible decision outcomes are fixed starting from the set-point and bounded to the interval X by its boundaries X^*, X_*. The probability of each outcome varies in each measure and formally, it can be expressed as

$$(X^*, P_e; X_*) \tag{3}$$

This lottery is made equivalent to the binary lottery by adjusting the probability P_e. In practice, the binary lottery with P_e is compared to another binary lottery with P=0.50, with one outcome set at the worst end of the X interval. Formally, it is given by

$$(X^*, P_e\,; X_*) \sim (X_i, 0.50\,; X_*) \tag{4}$$

where X_i and X_* are the value under analysis and the lower bound of the X interval, respectively. Successive, (X_i, P_e) are presented until the equivalence between the two scenarios is obtained. With the assumption that $U(X^*) = 1$ and $U(X_*) = 0$, the probability P_e defines the utility of X_i as

$$U(X_i) = 2P_e. \tag{5}$$

Then, given n utilities for n attribute values, it is possible to approximate the overall utility function with a spline technique or with an exponential approximation with at least 3 known points as:

$$U(X) = a + bX^c \tag{6}$$

All the considerations that have been made in the past Section are still valid. Indeed, all the elicitation interview must take into account the human psychometric considerations such as:

- Nature of Interview;
- Context;
- Scale of response;
- Consistency and replicability.

Nonetheless the already mentioned interview procedures, it is important to underline the concept of bracketing. Bracketing is a special procedure used as stimulus to help people to find and understand equivalents, a task which is ordinary difficult. This is obtained by first suggesting an equivalent that is less than the maximum but almost certainly too high, and then asking if the person being interviewed prefers the equivalent or the test lottery. The answer is easy. Then, a second scenario is suggested, which is probably too low. The idea is to narrow the possible range of response by bracketing the equivalent, which lies somewhere in between the lowest and the highest. In particular, bracketing works in two major way:

- Focus the answer gradually, helping the respondent to exclude the easy cases and concentrate on the answer;
- Reach the answer from above and/or below.

4.3.2.9 Aggregation of multiple attributes: multi attribute utility theory

Typically, human being is not a single attribute decision maker, besides it is usual that decisions are taken with more attribute under consideration. This Section focuses on how to aggregate different attributes for a single decision maker, aiming to a correct balance among preferences. The measurement techniques will also be presented, while particular attention will be given to the interaction among different attributes. Before going into details with Multi Attribute Utility Theory (MAUT) as the recommended procedure, this Section introduces the classic additive approach, together with its own limitations. The additive approach is represented by the following simple expression

$$U(X) = \sum w_i U(X_i), \tag{7}$$

where w_i is the i-th attribute scaling factor and X represents the **multi attribute utility.** Nonetheless the easier approach, the weighted sum of the utilities for an individual attribute ($U(X_i)$) has a fundamental limitation that makes it unappealing in practice: the additive model cannot express the value of any interaction between different objects. This neglects the several interactions among the several attributes of a system.

Pit Stop
When dealing with multiple attributes, the additive model neglects all the interactions among attributes, this is a major weakness because there is generally considerable value (either positive or negative) to the interaction among attributes. Attributes can be antagonist or complementary leading to an actual utility that is either greater or less utility then the sum of their parts**.**

Another weakness can be identified in the weighting methods. Nonetheless its attractiveness, ranking the attributes in order of importance as the classic approach when the sum of all weights is equal to zero lead to a worthless analysis. Indeed, the classic approach ignores all the possible trade off among attributes. It implies that any advantage on the first attribute, however small, outweighs all advantages on the other attributes. It thus implies that the lower ranked attributes might be worthless.

Pit Stop
Classic ranking approach might bias the trade-off process, any advantage on the first attribute, however small, outweighs all advantages on the other attributes, thus leading to a worthless analysis**.**

Aiming to a formal expression for multi attribute aggregation, it is necessary to consider two assumption: (i) preferential independence; and (ii) utility independence. The former, i.e. the preferential independence, can be esribed as:

The ranking preference of any pair of attributes is independent of the other attributes' values.

The preferential independence does not imply that some attributes are more or less important than others, besides it verify that the raking between two attributes does not change because of changes in the level of other attributes. Human beings are usually preferential independent but, in the contrary, they can be handled by eliminating all the alternatives with levels of attribute that fall below a required threshold.

On the other hand, utility independence can be state as:

The intensity of a preference (or lottery results) does not change in the presence of other attributes.

This implies that the "shape" of the utility function over an attribute does not change in presence of another attribute. The risk (aversion or prone) behaves over an attribute is still the same independently from the other attributes. With this assumption, it is possible to measure the way the utility changes over one dimension independently to all other attributes. Moreover, this independent measure can be combined to give a multiturbine utility function. Furthermore, human beings are usually utility independent and a person who is preferentially independent over attributes is almost certainly utility independent. If the assumptions of preferential independence and utility independence are satisfied, the value of the aggregate utility is given by

$$KU(\boldsymbol{X}) + 1 = \prod(Kk_iU(X_i) + 1) \tag{8}$$

where $U(X_i)$ is the utility relative to a single attribute, $U(\boldsymbol{X})$ the aggregated utility, K is the normalizing factor, which guarantee the contingency, ranging between 1 and 0, between $U(X_i)$ and $U(X)$, and k_i is the i-th individual scaling factor for each attribute, which defines the relative preference of the stakeholder among the different attributes.

To better understand the effectiveness of the MAUT formulation, it is useful to reduce the problem in the case of 2 attributes. In this scenario, after some simplification, it is possible to obtain the following formulation

$$U(X_1, X_2) = k_1 U(X_1) + k_2 U(X_2) + K k_1 k_2 U(X_1) U(X_2) \tag{9}$$

From equation 9, it is possible to see that the MAUT is the weighted sum of the one-dimensional utilities modified by terms accounting the interaction among attributes.

Pit Stop

MAUT is the weighted sum of the one-dimensional utilities modified by terms accounting the interaction among attributes**.**

As it has been introduced, the normalizing factor *K* ensures the contingency among multi-attribute and single-dimension utility. Substituting the corner constraint $U(X^*) = U(X^*) = 1$, it is possible to obtain the following formulation for the *K* factor

$$K + 1 = \prod (Kk_i + 1) \tag{10}$$

The factor *K* value is actually bounded by the sum of the k_i scaling factors. Thus,

- $\sum k_i < 1$ implies $K > 0$;
- $\sum k_i > 1$ implies -1 <K<0;
- $\sum k_i = 1$ implies $U(\boldsymbol{X}) = \sum k_i U(X_i)$.

The special case the sum of the individual scaling factor is equal to 1 entails a degeneration of the multi-attribute utility in the simple addictive model. Unfortunately, the k_i that is obtained from people rarely add up to 1.

The measure of the single scaling factor can be obtained by a special procedure called the *corner point procedure*. Within this procedure, each k_i is obtained considering k_i as the multi-attribute utility of the best level of its attribute *i* when all the other attributes are at their worst level. This procedure, integrated with the lottery equivalent procedure, aims to elicit the relative attribute importance thanks to the worst-case stimulus supported by confirmation bias. Last, it is important to notice that the measure of single utility is fundamental to a successful construction of the multi attribute utility function.

Once the utility related to each attribute has been measured, it is possible to evaluate the aggregated utility thanks to the Multi Attribute Utility Theory (MAUT). Indeed, MAUT aggregates single-attribute utility function into a single function that quantify how much different attributes are preferred from the decision maker, considering the different level of each attribute, guaranteeing the traceability of the effect related to each decision metric. By working with utility functions, instead of sets of preferences, the rational choice of a decision maker is to maximize utility.

4.3.2.10 The tool: Artificial intelligence-based tool for stakeholder interview and utility elicitation

Following a structured interview process inspired by uncertainty management such as lottery equivalent probability methods, it important to notice that, nonetheless many measurements of utility contain mistakes made by the interviewer, an experienced interviewer can avoid introducing biases into measurement of utility. The interviewer can be consistent when asking a question and can obtain reliable results with low margins of error. Unfortunately, this requires skills that are not ordinarily available.

Within this research, an interactive Expert Systems (ES) has been developed and applied (see Section: 4.2) to provide the means to avoid these errors and to insure consistency and reliability in the measurements. Indeed, if infused by the proper knowledge about how to manage an interview and taking into account the significant skills of an interviewer, expert systems show several benefits with the interview process. In addition, it is possible to underline features that improve the measurement: (i) ES are totally consistent and cannot bias the response by the different ways a person might present the questions; (ii) people being interviewed also tend to feel more comfortable working with a machine than with a person, since they can suspect that the interviewer may be judging them; (iii) ES encodes data instantaneously, avoiding the task of transcribing answers; and (iv) results can be processed instantaneously to provide an immediate feedback, i.e. plotting the utility functions as depicted in Figure 58. Last, exploiting the understanding of people's risk behave within the analysis of utility function, ES are able to autonomously exploit the lottery equivalent probability and bracketing techniques in order to elicit actual stakeholders needs by creating an ad-hoc uncertain scenario around develop interview questions. The system is also able to store the gained knowledge about the current stakeholder, aiming to a successive reuse and guaranteeing a faster interview and a continuous training for the AI algorithm.

Overall, research has demonstrated that interactive computer programs for measuring utility reduce the possibility of error as can be found in [104]. Figure 58 shows a snapshot of the developed graphical user interface supported by expert system. In the outcome of this analysis, the stakeholder is able to agree or disagree with the shape of the utility function relative to a single attribute. With this approach, the AI algorithm is also able to adjust the interview process to best capture and model the needs of a stakeholder, enhancing his/her elicitation techniques. The tool is able to exploit stored knowledge database related to most common attributes in space mission development but will store eventual new attributes if introduced by the stakeholder.

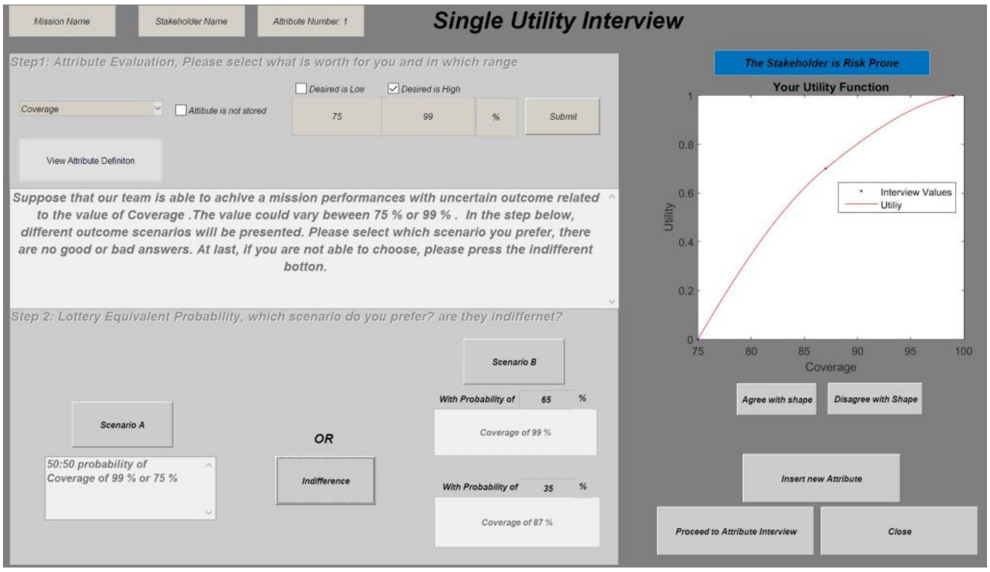

Figure 58 Utility elicitation guided by Expert Systems: Graphical User Interface

Once the single utility interview process is completed, it is request to the stakeholder to reply to a final questionnaire, as displaced in Figure 59. This last interview follows a corner point approach, in order to evaluate the independence of each attribute, validating the MAUT application. In case of dependence, the expert system will give a warning to the system engineer in order to allow to handle the attributes avoiding any kind of dependences among them.

The tool, developed in Mathworks Matlab environment, can be sent to stakeholders or, presumably, can be used during a pre-study session in “real-time”, with the stakeholder. This interview approach is able to speed up all the interview and needs analysis processes. Nonetheless, it is important to underline that, as expressed in Section 4.2, the developed algorithm will still need a knowledge engineer for maintenance and training propose. The application and test cases led to promising results as every AI algorithm, training time and application will let the algorithm to converge to desired behave.

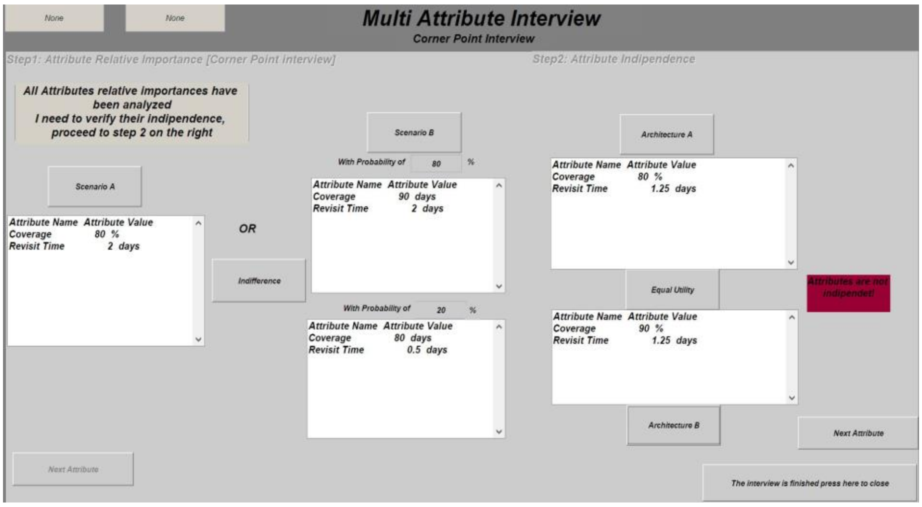

Figure 59 Multi Attribute interview assisted by Expert Systems: Corner point method

Pit Stop
Artificial intelligence in the form of expert system resulted an adjoined value for stakeholder interview processes, in specific: 1) ES are totally consistent and cannot bias the response by the different ways a person might present the questions, 2) People being interviewed also tend to feel more comfortable working with a machine than with a person, they can suspect that the interviewer may be judging them, 3) ES encodes the data instantaneously avoiding the task of transcribing answers. 4) Results can be processed immediately to provide an immediate feedback

4.3.2.11 Application to the case study

"The initial problem is never the real problem"
- Unknown

Following the identification and mapping of principal stakeholders involved in the development of the project, the next task is related to the elicitation of needs and attributes. It was shown in the previous Section that stakeholder needs, as all human needs, are usually characterized by high -evel uncertainties, especially in the problem definition phase. Nonetheless, the customer clearly expresses mission context, high-level requirements and constraints (see 4.1*), the initial problem is never the real problem*. Thus, the methods introduced in the previous sections have been applied to elicit principal stakeholder needs and translate them into mission attributes. Table 10 summarizes the results obtained from the first iterations with stakeholder needs analysis.

Table 10 Stakeholder analysis and interview: identified stakeholders, needs and attributes

Stake-holder	**Classification**	**Needs**	**Attributes**
Customer	Promoters (high interest and high decisional power)	To limit launch cost	Launch mass
		To push current TRL for CubeSat technology	Autonomy level
		To limit efforts and cost for communication with the lunar CubeSat.	Communication architecture
		To limit mission cost	N° of spacecrafts Autonomy Level Mission lifetime
Science	Defenders (high interests, medium decisional power)	To have reliable science data	N° of spacecraft Orbit stability Constellation type
		To map the radiation environment around the Moon at different altitudes and latitudes. To enhance the likelihood of GCRs detection and measure the effect on bio-payload	Orbit altitude Orbit inclination Orbit Stability Moon Coverage Mission Lifetime
Supplier & system designers	Defenders (high interests, medium decisional power)	To reduce maneuvers in order to limit tank volume and accommodate more bus/payload volume	Orbit Stability N° of maneuvers
		To accommodate payload and subsystems	CubeSat form factor
		To provide sufficient communication time and range with the orbiter in order to guarantee a successful data/command downlink and uplink	Orbit geometry N° of spacecraft

Once that the stakeholder needs and the relative attributes have been identified, the follow-up task involves a structured interview process. Considering the advantages and disadvantages of different stakeholder interview methods highlighted in Table 9, an internet web service has been applied. In particular, to overcome the disadvantages and to increase the control over the survey, Google questioner® has been chosen. Since the MONET methodology is aimed at handling multi-stakeholder problems, a questionnaire for each stakeholder has been developed. Hence, the identified attributes have been evaluated as of interest of one or more stakeholders. This activity will give a first outlook to which attribute will be negotiated between stakeholders or will be under observation by a single stakeholder. The allocation of attributes to stakeholders also assists to the generation and evaluation of questions within each developed questionnaire.

Table 11 Summary of identified attributes and owner

Attribute	Stakeholder
Orbit Stability	Science, Supplier
Minimum orbit altitude	Science
Maximum eclipse time	Supplier
Maximum sunlight time	Supplier
Sun ascension	Supplier, Science
Sun declination	Supplier, Science
Maximum access to the orbiter	Supplier, Customer
Minimum access to the orbiter	Supplier, Customer
Average revisit time (polar region)	Science
Average revisit time (equatorial region)	Science
Average time to cover	Science
Constellation geometry	Science, Customer
CubeSat form factor	Customer, Supplier
Communication Architecture	Customer, Supplier
Number of Satellites	Customer, Supplier
Autonomy Level	Customer, Supplier
Mission Lifetime	Customer, Supplier
Manoeuvre time	Customer, Science

Questions have been asked considering probabilistic questions with ranking structure in order to elicit and model single utility functions for each identified mission attribute.

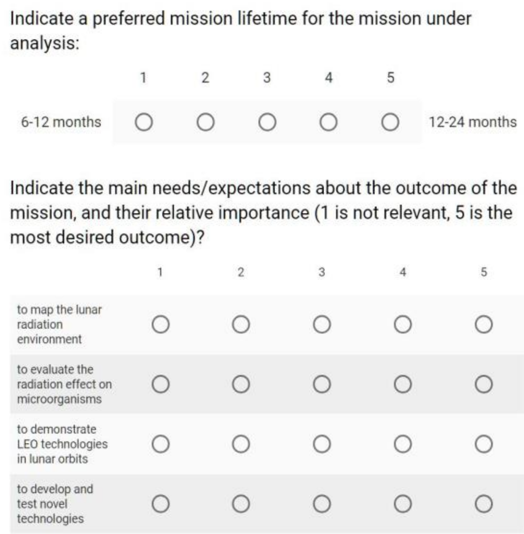

Figure 60 Interview process via Google Docs

Google docs allows to have a real time analysis of the interview results, as shown in Figure 61.

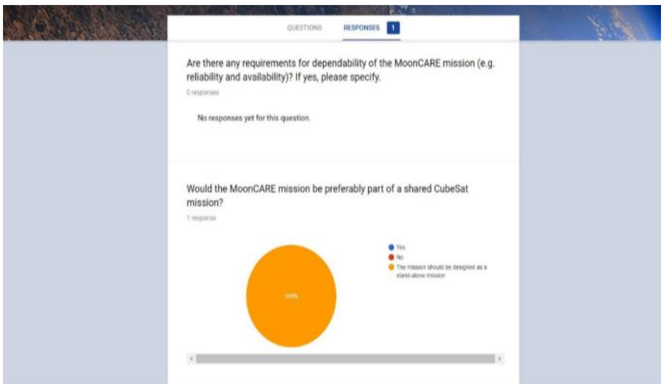

Figure 61 Results analysis through google docs

From the analysis of the question answered by all the stakeholder and form the distribution of the derived attributes to the stakeholder, it was clear that in the problem under analysis, some attributes utility functions consist in an actual means of negotiation. As an example, Figure 62 shows the elicited utility function related to the total number of satellites in the space segment of the mission architecture. It results clear that, from a scientific point of view, more the number of launched satellites increases more the utility increases. On the other hand, in order to reduce the launch cost, the trend is the opposite for the customer, i.e. launch provider. Hence, the next task involves the search for a solution to analytically handle this negotiation problem.

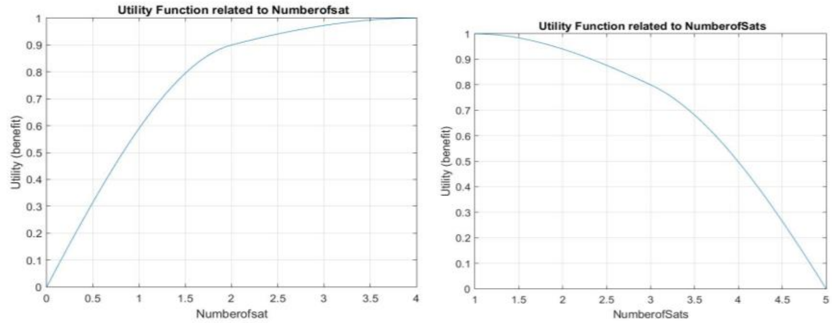

Figure 62 Conflicting Utility Functions: Scientific stakeholder (on the right) and customer/launch provider (on the left).

4.3.3 Group decision making and negotiation process

The decision-making scenario becomes more complex in the case of multiple decision makers, especially when attributes are of interest of more than one stakeholder. Thus, they need to be negotiated in order to find a balance between the parties. In this case, it is important to consider all group dynamics and social interactions among the people, who are building the group. A current field of decision-making research is focusing on how to aggregate preferences from different decision makers to obtain a balanced and universally accepted choice. This kind of collaborative decision making represents the most difficult form of system analysis and design, since the design that is the best for group members with different interests cannot be easily modelled analytically. There is no way a universally acceptable utility function can be defined for all groups and people in a decision. In this scenario, the recommended approach is to adapt collaborative negotiation, which permits the different group members to progress towards a mutually beneficial improvement.

The key hypothesis that allows multi-stakeholder aggregation relies on the fact that different stakeholders are closely connected, thus characterized by information exchange, trusted communication, and common "high-level" objectives, all aspects that are quite common in the design of space mission, especially in a concurrent engineering team. These hypotheses allow negotiators to avoid the conclusions of Arrow's Theorem reported in [105]. In this context, the Arrow's Theorem can be reformulated as follows: *there is no way to aggregate multiple stakeholder's utility functions without having the resulting function displays some irrational choice behaviours*, *when compared* *to the group of functions individually*. However, strong connected stakeholders can avoid this conclusion due to their individual interests are secondary when compared to the group as a whole (see [106] for further details).

Pit Stop
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4.3.3.1 The formulation issues

As previously introduced, an analytical formulation cannot be found in the case of group decision makers. In this Section, the major motivations of this statement will be explored, and the concept of group utility will be introduced. The utility function for a group is known in economics as *social welfare function*, which can be simply seen as the common good of a group[107]. Thus, it should depend on the ethical concept of a group.

Pit Stop
The utility function for a group is known in economics as *social welfare function* which can be simply seen as the common good of a group, thus it should depend on the ethical concept of a group.

At a first look, the social welfare function (SFW) can be modelled as a function or as different utilities for different individuals of the group. It is possible to suppose that, in a group that values each member equally, the SWF might be imagined as summation of the member utilities U_i as

$$SWF = \sum U_i \tag{11}$$

But groups usually value some people needs more than others. It might depend on social level, psychological biases, corporate hierarchy level, etc.. These concepts might suggest an alternative SFW formulation as a weighed sum, with w_i the weight related to the i-th member, of each member utility U_i

$$SWF = \sum w_i U_i \tag{12}$$

This formulation implies that great joy of some counterbalances the misery of others, which is in contrast with the concepts of social justice and equality. The suggestions can proceed without never reach a balance of analytical formulation thus, there is no way to transform everyone's utility into a common denominator.

Pit Stop
There is no way to transform everyone's utility into a common denominator. It is impossible to compare interpersonal utilities. The only way to define value for the group is to consider the values of its members**.**

To conclude this discussion, it is necessary to introduce with little more details the "Arrow Paradox" which argue the following aspects of group decision making, as reported in [106]:

- The choices of the group depend on its internal rules for decision making;
- No one voting rule or decision-making process is intrinsically the best;
- The choices made by a group are necessarily an ambiguous reflection of its preferences, so that one cannot rely on a group's choices to construct its social welfare function;
- The details of negotiation procedure will change the outcome of a group decision, the option that emerges as preferred from a paired comparison depends absolutely on which pairs is considered first

It is now clear that, when facing a group decision making, several issues must be considered. It is not possible to establish a social accepted group utility function due to the differences and uniqueness of everyone building the group. An effective methodology to obtain a convergence of the single values, both technical and non-technical, aiming to a unique accepted equilibrium is introduced in the following Sections.

4.3.3.2 Distribution problem

In collective decision making, it is important to consider the distribution of the decision-making abilities to each team member. The distribution and the attribute in analysis define the utility of each member and, thus, his/her contribution to the social welfare of the group. This becomes evident when the design of a mission is considered as the combination of group member's technical aspects and interpersonal values modelled as objective cost and subjective utility. This is the distribution problem, i.e. the determination of what utility each member of the group will obtain at the end of the design process and in which attributes he/she might has control.

Pit Stop
Since the only way to define value of the group is to consider the utilities of its members, the distribution problem investigates the determination of what utility each member of the group might get from the design solution to define a negotiation strategy.

At first, it might seem logical to "maximizing the pie", the more pie each member has, the easier it would be to make everyone happy. On the opposite, in the analysis of complex and interconnected systems, it has been proved that the maximization of a single value often does not and cannot lead to the best solution for the group. Maximizing the powerful stakeholder's utility, leaving the designers worrying about the "rest", not only is quite different from the social welfare optimum, but in fact impedes it. Even if the maximum value of the gained utility and the total budget of the mission are fixed, the goal is to achieve mutually beneficial improvements in the distribution of utility among team members. The aim is to find a solution that is not a zero-sum-game. Nonetheless, the resources are fixed, and any advantage of a person might not imply disadvantages from all the others, because the differences among stakeholders might provide mutually beneficial opportunities. This analysis would be correct in the case of simple system, when interconnections are not under analysis. The reason why it is possible to obtain mutually beneficial improvements is that, in the case of shared variables, each individual subjective values each product differently. There should be opportunities for trades that benefit both. Trading among individuals allow them to achieve balanced distribution that maximize their mutual utility. This trade must be structured and well performed in order to obtain an effective equivalence of utility and a sub-optimal condition for the social warfare function. The collaborative negotiation could assist with this tedious task.

4.3.3.3 Connected stakeholders and aggregation methods

Before concluding the exploration of the issues involved with a group decision making and proceeding with an analysis of its possible solutions, it is necessary to introduce group decision styles. In a group, depending on the social hierarchy structure or member decisional power, different decision styles can be applied. Many large engineering design efforts feature tightly connected stakeholders. These stakeholders are responsible for advocating for their own interests but are ultimately subject to the will of the entire group and lack the ability to withdraw from the design process. As an example, let consider a project organized into subsystem design teams: each team must satisfy their own needs, but they all must come to an agreement because they work for the same company/organization. The most common means of addressing multi-stakeholder decisions of this type in the systems engineering field is by simply aggregating the requirements of each stakeholder (see section 1.5 for more details). Given the difficulty inherent in estimating value for complex systems, often stakeholders must iteratively update their value statements as new information becomes available. This limits the applicability of voting or bidding mechanisms for multi-stakeholder decision making on complex systems.

The field of collaborative engineering would refer to this high degree of interaction between stakeholders as either collaborative or cooperative (as opposed to the less-connected coordinated). In particular, collaborative negotiation has received significant attention in recent years as shown in [32]. Table 12 highlights the key differences between these categories of human interactions.

Table 12 Team members interaction typology

	Stakeholder	**Resource**	**Goal**	**Task Structure**
Coordination	Large community	Limited and Exchanged	Multiple and competing	Pre-defined, same layer in hierarchy, unidirectional
Cooperation	Mid-size group	Limited and Shared	Multiple and private	Pre-defined across layers in hierarchy, bi- direction
Collaboration	Small team	Limited, Shared, Complementary	Single & common	Undefined, non-hierarchical, multi- direction

The difference between the three types of attitudes relies in the nature of the goals of the involved stakeholders. Collaboration implies a common goal, while cooperation considers different goals, and coordination hidden goals. However, collaboration is not a superior form of partnership, as one might assume due to its higher degree of interaction and alignment of goals. Rather, it is an artifact of the nature of the project and the relationship of the participating stakeholders. Many stakeholders do not engage in collaboration, but rather work together with much more limited information exchange and distinct preferences. This shift towards coordination is particularly evident when stakeholders are not tightly connected but rather independent, as discussed later.

In collaborative design, it is important to consider *multiple decision-makers and multiple objectives*. For complex design organizations, comprehensive, centralized decision-making exceeds the limits of human rationality. Typically, collaboration among multiple actors with different objectives is seemed by *ad hoc* ways, such as team meetings, notices, or information exchange. These techniques are effective to some extent in practice, but they do not provide formal support for formulation and integration of the individual decisions that mark the progression of a design. In the following Section, a possible solution for the collaborative decision-making formulation can be found in the so-called game theory.

4.3.3.4 Idea Generation and design vector generation

"I have not failed. I've just found 10,000 ways that won't work"
-Thomas Edison

The next task within the MONET framework consists in the generation of design alternatives through the derivation of design parameters from identified attributes. The idea is to have a continuous link from identified needs and attributes to design parameters, which must be derived according to the multi stakeholder environment. There is no right way to generate design alternatives, but the standard process, as shown in Figure 63, is the closed-loop generation process: revaluate and think it over are the basic tools for generating and evaluating a good idea and related solutions.

In this Section, the principal "Man-in-The-Loop" idea generation techniques are described.

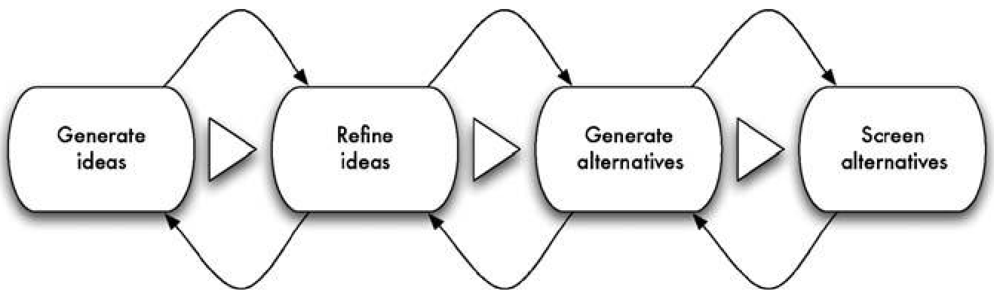

Figure 63 Idea Generation Process ([66])

Once that the design vector elements have been defined, it is also mandatory to evaluate its boundaries. For this process, as inspired by the CML push, the expertise of the design team is the driver for the process. Indeed, once defined the high-level requirements and mission objectives from the stakeholder analysis tasks, it is possible to evaluate design variable boundaries via similarity with past missions or the state-of-the-art. Then, the expert is allowed to vary past values according to his/her expertise in order to better explore novel solutions within the trade space. The introduction of AI based expert systems is foreseen in order to automate this process, assisting the expert in the definition of design variables and tradespace boundaries.

4.3.3.5 Idea generation techniques: Brainstorming and Delphi methods

One of the most popular and effective methods to generate ideas can be identified in the brainstorming and Delphi methods as suggested by [66], [108]. Those methods are exploited, or it is strongly suggested its application, within the MONET design methodology. The decision between the application of Delphi methods or brainstorming depends on the available time and the people within the team.

Brainstorming is a technique based on the concept that a group of creative thinkers can create a pool of ideas that will contain the insight of a solution. It adopts the concept that two heads are better than one, or how it is called in early operation researcher, the n-heads rule. The unique outcome and goal of a brainstorming session is the generation of a list of ideas. The brainstorming technique was developed by advertising executive Alex Osborn in 1941, who noticed that conventional business meetings were carried out in a way that creativity and ideas struggled to efficiently come out, as reported in [109]–[111]. Osborn drawn the following four basic rules for conducting a brainstorming session, which will be used during generation of ideas:

- *No Criticism of Ideas*. Participants shall feel free to express all ideas without fear of judgment.
- *Encourage Wild and Exaggerated Ideas*. Wild ideas usually contain unique insight from which a design solution may be built upon. This kind of ideas will be later on during tradespace exploration.
- *Seek Large Quantities of Ideas*. Brainstorming sessions concern fast iterations and spontaneous behave. Ideas might also trigger other ideas.
- *Build on Each Other's Ideas*. Ideas exposed by one person's perspective often elicit new ideas from others.

Brainstorming sessions generally might be organized in two forms: structured, unstructured (free form). The main difference between the two forms is the level of control by the session manager, who may combine any of the three to meet problem needs.

On the other hand, Delphi method, invented by Olaf Helmer and Norman Dalkey in 1953 to address specific military problem, is aimed at minimizing the biasing given by dominant people and misleading information. Delphi introduces three variations with respect to the classic brainstorming [112] as:

1. Anonymous response when possible.
2. Iteration and controlled feedback: information control and processing among iterations.
3. Statistical group response: aggregation of individual response.

Delphi methods are also different from traditional brainstorming due to their strong dependence on discipline experts. In this case, sessions are typically structured in 10 basic steps, as illustrated by Fowles [113]:

1. Form the team to prepare and screen the session.
2. Select one or more group of experts that will actively participate.
3. Develop the first-round questionnaire.
4. Verify the questionnaire for proper jargon.
5. Submit the first questionnaire to the participants.
6. Analyze the first-round responses.
7. Prepare the second-round questionnaire.
8. Submit the second questionnaire.
9. Analyze the second-round responses. Repeat steps 7 through 9 as necessary.
10. Prepare the final report related to the findings.

These structured 10 steps point out another benefit: it is not requested that the *participants are in a central location*. However, this has also an important drawback. A Delphi session, in which there is not sufficient involvement by participants or is bad executed, may be characterized by frustration or lack of focus. Other criticisms of this technique are related to the nature of the expert opinion. In some cases, it might occur that an opinion of experts is structured as fact rather than as opinion, so the session manager may bias responses by a-priori selection and filtering of questions. A framework inspired by the Delphi method is also exploited to handle stakeholder objectives ambiguity as presented by Golkar et.al [114]. Summarizing, selecting the right questions is the key for Delphi and brainstorming sessions success.

4.3.3.6 Case Study: definition of design variables in the case of multi-stakeholder environment

The next phase consists in the problem set-up, a list of design variables has been derived and the boundary of their possible variation has been evaluated exploiting a brainstorming session. The session manager highlighted customer technical constraints and high-level requirements. The brainstorming team was composed by PhD students and professors. All the ideas have been iterated in order to understand if a design variable would be demanding for some identified stakeholder attributes and needs. Table 13 summarized the outcome of the brainstorming session, which also underlined the decisional power of each stakeholder related to the design vector elements. The structured brainstorming session was also aimed at the understanding of design variable owner. Indeed, design variables could be negotiated or in charge of only one stakeholder.

Table 13 Design Variables

Design Variable	Alternative 1	Alternative n	Stakeholder	Type
Orbit Type	Circular	Elliptic	Customer, Science	Negotiated
Circular orbit Altitude	50 km	600 km	Science	Local
Elliptic Orbit periapsis altitude	50 km	200Km	Science	Local
Elliptic Orbit apoapsis altitude	500 km	600 km	Science	Local
Inclination	50	90	Science	Local
Right ascension of ascending node	0	360	Science	Local
Communication architecture	Orbiter inter-link or Earth direct downlink	Orbiter and Earth direct downlink	Customer, supplier	Negotiated
CubeSats interlink	No	Yes	Supplier	Local
CubeSat Form Factor	6U	12U	Supplier	Negotiated
Number of Satellites	1	4	Science, Supplier, Customer	Negotiated
Autonomy Level	1	4	Supplier	Local
Mission Lifetime	6 Months	3 Years	Customer, science	Negotiated

Design variables influenced mainly system architecture, with attention to the orbital parameters. Due to the constraints related to the total mass to launch and, on the other hand, to the need of observing as much lunar surface as possible, the number of satellites and the CubeSat form factor have also been identified as design variables to be traded. The allocation to interested stakeholders and the identification of the nature of the design variable between negotiated and local owned have been carried out in accordance to the identified stakeholder.

4.3.4 Building and exploring the negotiation space

Once the problem has been properly settled, the next task within the MO-NET methodology involves the creation and exploration of what is here named Negotiation Space. This Section will go into details in group decision making and negotiation within engineering design, deriving the equations in order to guide these negotiation processes while avoiding the violation of the

Arrow paradox. The optimized exploration process is aimed at finding a mutual set of design alternatives, which are “optimal” or “sub-optimal” in the sense of equilibrium of stakeholder needs. With this porpoise, game theory, multi-attribute utility and multidisciplinary optimization are exploited to efficiently build and explore the negotiation space.

4.3.4.1 The problem of negotiating in engineering design

Several techniques are currently adopted to obtain collaboration among multiple stakeholders, such as team meetings, notices, or information exchange. Despite the proven effectiveness of these collaboration techniques, engineers still spend about 10% of their time negotiating and it represents one of the most frustrating phase of the design process. On the other hand, negotiation is essential in order to propose a socially accepted and efficient point design. Unfortunately, as previously introduced, there is no way to analytical derive a social welfare function due to the impossibility of making interpersonal comparison of utilities. Thus, it results quite demanding infusing the negotiation processes within analytical tools for engineering design.

Among negotiation processes, triggering collaboration is also important because of the huge possibilities of mutual gain among team members. Changes in the allocation of benefits are central for mutually beneficial improvements. These are achieved by exchanges between individuals. A key aspect of negotiation consists in finding opportunities for these exchanges. Trade-offs can be made between different levels of risk attitude. Some members of the group may be quite reluctant to accept risks when others are not. This provides the opportunity for exchanges between the two. Last, an almost inevitable characteristic of collective decision-making is that the smaller members of the group get a larger distribution of benefits than their proportional share per size. This fact is counterintuitive: one might expect that the powerful members get their own way and exploit the weak. Indeed, *the strong dominates the weak when results are determined by brute force.* But the reverse is true as well when collaborative decision making is considered, where each member of a group has vote on the final design. The reason why the bigger is get exploited is that they have great deal to gain from collective strategies and actions. Therefore, aiming to ensuring a collective decision, the bigger ones are willing to trade relatively generous to the small team members, who may not have as much to gain.

Summarizing, the outcomes of negotiation process must be modelled at two levels. First, the result depends upon the voting results and the group decision style, infusing stakeholder's risk behave and attitude in collaboration. Secondly, as it has been explained by the Arrow paradox, small procedural features can make a substantial difference to the outcome, the dynamics of a decisional group must be properly modelled. Finally, personal style influences the results of trading. Abrasive, aggressive approaches may seem to be effective but often fail in achieving the significant gains that can result from collaborative negotiation.

4.3.4.2 Modelling negotiation dynamics: Introduction to game theory

Among different methods currently employed to handle negotiation and group decisional problem (e.g. meetings, emails), game theory results a valuable tool to put the basis to answer the research question Q2.1:

Q2.1: How can we assist team of interconnected stakeholder in early decision-making phases? Is it possible to model and optimize the negotiation processes in a reliable way?

Human beings are strategical creatures since the dawn of time, or at least they should be. Indeed, some concepts of "intelligent" life involve the ability of thinking "strategic." Game theory is a theory of independent choice founded by Von Neumann in 1928 [115]. Game theory studies interactions between self-interested actors called players. It focuses on the problems of how interaction strategies can be designed in order to maximize the social welfare by assisting team decisions and strategy in order to find the so called "equilibria". One of the most important assumptions of game theory is that actors are rational players. In game theoretical models, it is assumed that rational players act to maximize their utility. If any player follows a dominant strategy, he/she will gain the best payoff, no matter how the other player(s) will act. With these assumptions, a dominant strategy is the optimal strategy for a player, independently from what the other player(s) does. Nonetheless, the actual aim of game theory is to find a condition of equilibrium among players. An equilibrium in game theory is defined as a social accepted outcome, with respect to the payoffs gained by each player at the conclusion of a game. Usually, it is possible to define the equilibrium point as stable because, after players accept an equilibrium point considering their payoffs, they don't have incentives to deviate from that point: this is the solution of the game.

There are four principal equilibrium concepts[116]:

- *Dominant equilibrium*: each individual option is the best for the corresponding player, no matter what options the other player chose. Dominant strategy is a strategy that is better than any other strategy a player can choose from his set of actions. When is identifiable, this creates the potential for an equilibrium position among multiple players.
- *Nash equilibrium*: if any single agent change its decision, this would reduce his/her level of satisfaction. This is the strategy in which players always play with no regrets. In a two-player simultaneous-move game, a pair of strategies is called a Nash equilibrium if the choice of player 1 is optimal based on player 2's choice, and player 2's choice is optimal based on player 1's choice. A game has a Nash equilibrium if there exists a set of strategies such that each player optimizes his/her utility given the other players' actions.
- *Stackelberg equilibrium*: in the case of one player dominating the other, i.e. leader-follower game in which the leader moves first, this type of equilibria occurs when any agent changes his/her decision, thus reducing his/her level of satisfaction. If a game is a non-simultaneous (sequential) game, the first mover has the advantage and is able to dictate an equilibrium.
- *Pareto equilibrium*: no single agent, by changing its decision, can increase his/her level of satisfaction without lowering the satisfaction of at least one other player.

If the players are disposed to cooperate, they may seek a Pareto equilibrium. However, in a game, a self-interest player would have no incentive to choose a Pareto equilibrium unless he/she would join a coalition. The concept of Nash equilibria is consistent with an attitude of exclusive self-interest and it is the most basic one of the stability criteria. If there is a set of strategies with the property that no player can benefit by changing his/her strategy while the other players keep their strategies unchanged, then that set of strategies and the corresponding payoffs constitute the Nash equilibrium.

Players can aim to a strategic advantage via the *response rule*. A response rule sets one player action(s) as a response to another player action(s). Response rules are prevalent in our daily lives. A manager telling an employee he/she will get a raise if he/she exceeds his/her sales plan for the current year is a simple example of a response rule. The response rule can be defined in two ways: threats and rewards. Threats are messages that players can give to each other to affect the other player strategy. With a threat, failure to cooperate results in some type of negative payoff. With a reward, cooperation results in some type of positive payoff.

In cooperative game theory, let's abstract from individual players' strategies and, instead, let's focus on the coalition players may form. Moreover, let's assume that each coalition may attain some payoffs, and then let's try to predict which coalitions will form. The non-cooperative case is significantly inferior to the solutions in the other approaches. Therefore, non-cooperation should be avoided at all costs. This, of course, is common sense. However, it has been supported in this Thesis using formal and rigorous decision constructs. Even largely sequential processes, as modelled in the leader/follower protocol, are shown to be more advantageous to the final design than the non-cooperative case.

4.3.4.3 Introduction to collaborative optimization

Multi-Disciplinary Optimization (MDO) emerged as a new field of engineering in the 1980s. It is a method for the design of complex systems that are governed by mutually interacting phenomena and made of distinct interacting subsystems. MDO uses optimization methods to resolve design problems by studying different disciplines simultaneously. Similar to the concept of CE, MDO explores the interactions among disciplines and empathies the harmony of the disciplines and subsystems. Thus, the optimum of the problem is more effective to the design found by optimizing each discipline in line. Therefore, under the MDO framework, the organization of the optimization problem is very similar to that of a concurrent design facility. This similarity makes MDO very suitable for industrial usage. Several conceptual components merge to form MDO, which consist of feasibility assessment, design-oriented analysis, approximation, system mathematical modelling, decomposition and human interface.

Among the different MDO architecture, the Collaborative Optimization (CO) framework results well fitted for a concurrent design environment. In CO, the architecture optimization is carried out at discipline and system levels. Thus, discipline feasibility and system analysis are guaranteed throughout the optimization process. The MDO problem is decomposed into a sub-problem according to each discipline involved in the study. The discipline optimization is carried out ensuring that local discipline constraints are satisfied. The system level is optimized with respect to global, coupling, and local variables. The constraints at the system level consist of global constraints as well as compatibility constraints of the discipline. The discipline optimizer, on the other hand, reduces the delta between the system level variables and the discipline variables. One significant advantage of CO architecture is that each discipline can be optimized in parallel. Furthermore, different optimization techniques (gradient- or non–gradient-based) can be used by different disciplines[82]. One of the disadvantages of CO architecture is that the dimensionality of the system-level optimization problem increases significantly with the increase in coupling variables.

The CO architecture at system level can be mathematically stated as the minimizer of the following function

$$f(z, y, x_{obj}) \tag{13}$$

with respect to the local, conjoined and objective variables z, y, x_{obj} subject to

$$J(z_i, z^*, x_{obj}, x^*_{obj}, y_i, y^*) \tag{14}$$

where x_{obj} is the local variable affecting the objective function.

4.3.4.4 Speed up exploration with Evolutionary Algorithms: Genetic algorithms and pattern search

In complex problems, as the conceptual design of a space mission can be, the number of solutions that form the design space can reach a impressive size. Therefore, it is mandatory to exploit structured and efficient ways to explore the design space and evaluate the solutions, in order to keep the computational cost and the exploration duration acceptable. Depending on how the problem is constructed in the first place, several different exploration methods exist, that can move through the space both in case of a continuous space and in the case of a discrete one. Examples of these methods can be genetic algorithms for discrete problems, or simulated annealing for continuous ones, as presented in [117]–[119].

The present work explores the use of Genetic Algorithms (GA), performing a type of exploration called *guided random search* (further details can be found in [82]). These types of algorithms are inspired by the natural selection process, which brings the stronger individuals to survive in a competitive environment. In nature, each member of a population competes for food, water and territory, and also strives for attracting a mate. It is obvious that the stronger individuals have a better chance for reproduction and creating offspring, while the weaker performers have lesser chances of producing offspring. Consequently, the ratio of the strong or fit individuals will increase in the population, and overall, the average fitness of the population will evolve over time. Offspring created by two fit individuals (parents) potentially has a better fitness compared to both parents: the resulting individual is called super-fit offspring. By this principle, the initial population evolves to a better suited population to their environment in each generation, as described in [120].

Population dynamics

In genetic algorithms, each solution of the problem is represented by a set of parameters known as genes, and these are joined together in a genome. A genome, which describes an individual, evolves through iterations called generations. The dynamics of each individual inside the population are ruled by a function that evaluates how well the considered individual performs in the environment it is in. The mentioned function is called fitness or objective function. Finally, during the various iterations, a selection of the parents for reproduction and recombination is applied [121].

The main objective of selection operator is to pick the fit solutions and to eliminate the weak individuals. In the reproduction phase, the two parents identified by the selection operator recombine to create one or more offspring with the crossover operator. There are several different crossover operators in the literature, although the underlying mechanics is similar: selecting two strings chromosomes from the mating pool and exchanging some portion of these two strings in order to create new individuals. The purpose of this operator is to perform a rapid exploration of the search space.

Another operator that can be applied is the mutation operator. It is applied to individual solutions after reproduction: one or more genes are randomly changed in an individual, after a selection has been applied. The mutation operator usually affects small portions of the population. The aim of this operator is to maintain the diversity of the population and to increase the possibility of finding the global optimum. To sum up, the selection operator selects and maintains the good solutions whereas the crossover recombines the fit solutions to create fitter offspring, and the mutation operator randomly alters one or more genes in the offspring with the intent of maintaining the evolution dynamic.

4.3.4.5 Formulation of the optimized negotiation process and negotiation space paradigms

This Section aims at finding an answer to the research question Q2.2:

Q2.2: Given the state of the art and the trend of systems engineering methods, how can we infuse negotiation processes within the tradespace exploration phases? It possible to have a user-friendly alternative exploration focused on social welfare?

Giving the methods introduced in the previous Sections, a so-called negotiation space is generated and explored. Before going into details with the characteristic of negotiation space exploration, a brief introduction about the negotiation space is given.

What is a negotiation space?
As a multi-variant mathematical play-space used for identifying the optimal group boundary design spaces (i.e. nash or pareto frontier), the negotiation space:

- results composed by the multi-attribute utility of each stakeholder and a social accepted metric;
- enables the exploration of different design alternatives from negotiation point of view

Based on the concepts within game theory, the negotiation space, in parallel to the analysis of several design alternatives from the negotiation point of view, allows the analysis of possible stakeholder's strategies towards a point of equilibrium. The strategies available to players to bring about particular outcomes can be decomposed into a sequence of decisions called choices, which are pictured in the stakeholder design vector choices. Players are assumed to be able to evaluate and compare the consequences associated with the set of possible outcomes and assign utilities to each outcome thanks to the adoption of MAUT.

Due to the dimensions of the negotiation space, multidisciplinary optimization might be explored to speed-up the process. Generally, according to game theory, the objective function of a stakeholder depends on the choices (actions, or equivalently decision variable) of at least one other player, and more in general, of all the players. Hence, a stakeholder cannot simply optimize his/her own objective function independently from the choices of the other players. This implies a coupling between the actions of the stakeholders and binds them together in decision making, even in a non-cooperative environment. If the players are able to enter into a cooperative behave (the selection of actions or decisions is done collectively and with full trust) in such a way that all players would benefit than cooperative game theory can be applied, which is typically the case of engineering design.

Due to the strict connection among stakeholders and the nature of the negotiation process, MDO has been applied in the form of collaborative optimization, as represented in Figure 64.

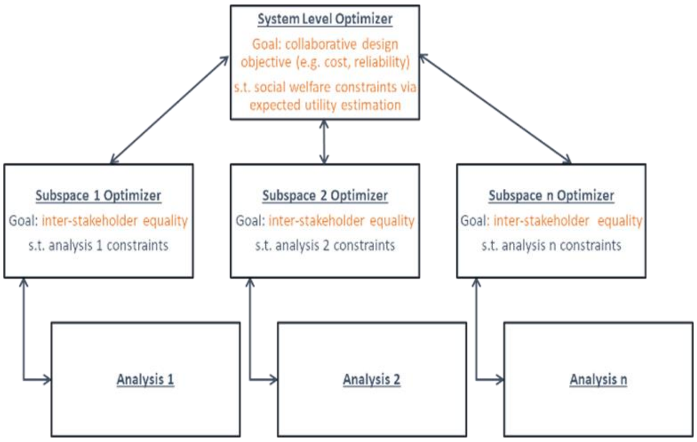

Figure 64 Collaborative optimization Architecture for multi-stakeholder problem

In order to properly model the dynamics of collaborative group negotiation, the expected utility can be used by the first level optimizer, i.e. the "negotiator", as a measure to simulate the negotiation process giving stimuli via a bid to sub-level stakeholders. In the realm of game theory, the most suited game approach to properly model this team dynamics is founded in the Stackelberg game. The Stackelberg game model is a bi-level strategic game (see Figure 65) born in the context of economics, in which the leader (first level moves first) and then the follower move adjusting his/her strategy according to the leader decisions, as described in [122], [123].

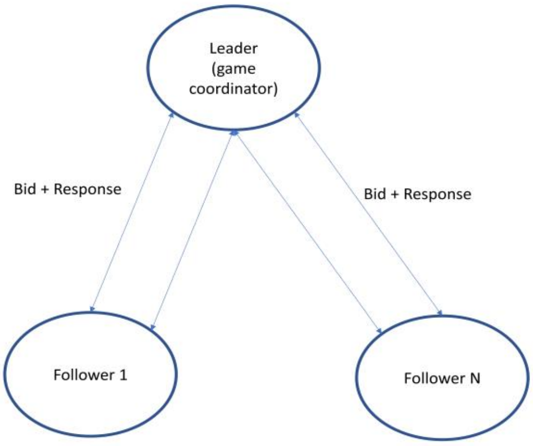

Figure 65 Stackelberg game architecture

Now, it is important to talk more about the Stackelberg equilibrium. To properly reach the stable equilibrium point, the leader must know a priori the information set related to follower. Indeed, in the case that the 'follower' commits to a leader action and the 'leader' is capable of knowing this, it is straightforward that the leader's best response would be to play a Stackelberg follower action. Moving observably first is the most obvious means of commitment: once the leader has made his/her move, he/she cannot undo it – he/she is committed to that action.

Thanks to the obvious similarity between collaborative optimization and Stackelberg games, the two methods are hereby combined in order to efficiently guide the bi-level games while understanding the dynamics and results throughout the optimization process. Stackelberg games have been applied for several applications, and the most notable for this study can be found in the multi-follower architecture with application of evolutionary algorithms described in [124] and the leaders with uncertain information set amount the followers, as depicted in [125], [126]. In this framework, the combined frame between collaborative optimization and Stackelberg game, i.e. the expected utility is evaluated by the negotiation, is estimated by attributes corresponding to other domain information and cooperation behave among stakeholders. From game theory becomes clear that social welfare function is influenced not only by decisions outcomes, but also the negotiation approach results influence the final team outcome. Throughout the negotiation process, stakeholders must accept, reject or counteroffer a request. To emulate this, each player keeps track of his/her own average reward and uses this reward to decide how much to charge for his/her own services and, occasionally, to approximate the expected average reward of other stakeholders. Hence, expected utility can be seen as a coordination tool in order to guide the negotiation process.

In the MONET methodology, the exploration of the negotiation space follows a quasi-collaborative game, in which the negotiator is modelled as a coordinator who has opponent stakeholders adjusting their strategies according to what they believe everybody else is doing. This dynamic is modelled by the expected utility, evaluated by the negotiator with respect to what is known about the preferences of the other stakeholders. Despite it is supposed that the negotiator is a separate entity, which coordinate the sublevels, it is important to underline that the architecture can be adjusted in the case of a strong hierarchy related to power and/or interest of the involved stakeholders. For example, if after a detailed stakeholder analysis (see section 4.3.1) , it is noticed that one stakeholder possesses more decisional power with respect to the others so that he/she must give the final verdict on the decisions, the negotiation architecture shall be adjusted. This adjustment can be done introducing the powerful stakeholder at the system level as negotiator. In this case, the first level, emulating the identified stakeholder, will optimize the negotiation, searching for an equilibrium, which will be biased by his/her own preferences.

Design variables and the problem of distribution of decisional power can be easily handled by a direct implementation of the outcome from the stakeholder analysis. Global variables are used by the negotiator in order to obtain a broad view of the negotiation process. Negotiated variables are overseen by the negotiator, whom, thanks to the broad view given by the global design vector, will take the final decision of the optimal value for the negotiated design variable. Therefore, negotiated design variables are constraints for the second level stakeholders. Moreover, local design variables are used by the second level stakeholder in order to reach a desired benefit despite the constraints given by the not owned or negotiated ones. Last, it is important to notice that, depending on the implemented decision style, it is possible to observe two different behaves regarding the negotiated design variables: (i) in case of stakeholder parity, the negotiator will explore values in order to obtain a balanced negotiation; (ii) in case of stakeholder prioritization, the negotiator (modelling the primary stakeholder interests) will explore alternatives but with a biased negotiation towards its own preferences.

Cost Functions

The selection of the cost functions is critical to properly model the problem and the dynamics within the negotiation process and it must be handled with caution. Concerning the goal of a collaborative game, it is important to select a social accepted variable to be optimized. Furthermore, the decision style shall be considered. Mainly, it is possible to identify two principal scenarios: (i) *stakeholder parity*: in this scenario, the negotiator shall optimize a social accepted design metric: If stakeholders agree with a design-to-cost philosophy, a common accepted variable could be identified in the total cost of the project; (ii) *stakeholder with higher decisional power*: the cost function will address the subjective preference of the powerful stakeholder (e.g. his own multi attribute utility): cost can be considered as additional objective to be minimized. As a result, it is important to carefully analyse the outcome of the stakeholder analysis in order to have a robust selection of the negotiation-level cost function.

The selected cost function introduces the concept of *collaboration constant.* This constant is measurable via a specific interview process. The measure approach shall be similar to the one used for the measurement of utility. It is important to set up the interview process with the aim of measure a collaboration value, even in case of uncertainties, and the lottery equivalent probability method with an ad-hoc proposed scenario is suited for the measurement. This cost function J_i can be described as follows:

$$J_i = c\left(E_{negoz}(\boldsymbol{X}) - U_{local}(\boldsymbol{X})\right)^2 + (1-c)U_{local}^2(\boldsymbol{X}) \qquad (15)$$

where c is the collaboration variable ranging between 0 and 1, $E_{negoz}(\boldsymbol{X})$ is the stakeholder expected utility estimated by the negotiator, and $U_{local}(\boldsymbol{X})$ is local stakeholder multi-attribute utility. In order to avoid direct comparison of subjective utilities, the cost functions try to model the negotiation process via the concept of negotiator expected utility. According to the information on stakeholders' preferences gathered during the preparation phase, either partial or complete, the negotiator tries to estimate the expected utility of a sublevel stakeholder. Then, the estimation is used as a bid for the subproblem, trying to optimize its design strategy and decisions with respect to the reply of the sublevel stakeholders pictured within the value of J_i.

The cost function is composed of 2 principal addenda, both function of the collaboration constant c: (i) the first term is a collaborative term, in which the sublevel optimizer tries to follow the expected utility of the negotiator; and (ii) the second term is a selfish addendum, in which the optimizer tries to develop a strategy to maximize its own utility. Both these terms are quadratic to obtain a robust optimization process and to increase each stakeholder's awareness of their influence on other disciplines and the global objective. Since there is not a comparison of interpersonal utility, but rather a bid on the estimation of expected utility, the Arrow paradox is not violated. Each stakeholder keeps track of his/her own average reward and uses this reward to decide how much to charge for his/her own strategy and, occasionally, to approximate the expected average reward of the other stakeholders.

Now, it is valuable to analyse the concept behind the zeros-searching of the optimizer. When looking for the minimum of the objective function J_i, it is possible to observe that the behave of the optimizer depends on the value of the collaboration constant c. In specific, explicating J_i and setting equal to zero, it results

$$U_{local}^2(\boldsymbol{X}) + cE_{negoz}^2(\boldsymbol{X}) - 2cE_{negoz}(\boldsymbol{X})U(\boldsymbol{X}) = 0. \qquad (16)$$

When a stakeholder is collaboration prone, i.e. $c = 1$, equation 16 can be simplified as:

$$\begin{gathered}\left(E_{negoz}(\boldsymbol{X}) - U_{local}(\boldsymbol{X})\right)^2 = 0 \\ \rightarrow\ E_{negoz}(\boldsymbol{X}) = U_{local}(\boldsymbol{X})\end{gathered} \qquad (17)$$

It is possible to observe that, in the case of collaboration prone, the minimization problem brings the sublevel optimizer to try following the negotiator expected utility, resulting in a classical leader-follower behaviour. On the other hand, in the case of null value, i.e. $c = 0$, the equation 16 becomes

$$U_{local}^2(\boldsymbol{X}) = 0, \qquad (18)$$

where the sublevel stakeholder is collaboration adverse, which behaviour is translated for the optimizer in a null value of subjective utility $U_{local}(X)$. Thus, the sublevel stakeholder cannot find benefits in either cases when tries to find group equilibria. It is possible to better understand the meaning of this results observing the case of null collaboration constant from equation 15

$$J_i = U_{local}(\boldsymbol{X}). \qquad (19)$$

Since the stakeholder is collaboration adverse, the optimizer will try to maximize the subjective utility, whatever it is the bid from the system level. The last case is represented by a collaboration constant between 0 and 1, in which it is possible to observe an interesting behave. Considering the point of equilibrium $J_i = 0$ in which both negotiator constraints and stakeholder needs are satisfied and evaluating the first derivate of the cost function (equation 15), it is possible to obtain two different results, depending on which variable the equation is derived from. If the equation 15 is derived with respect to the expected utility, it is possible to analyse the problem from the negotiator point of view, obtaining

$$\frac{\delta J_i}{\delta E_{negoz}(\boldsymbol{X})} = 0 \rightarrow \quad E_{negoz}(\boldsymbol{X}) = cU_{local}(\boldsymbol{X}) \tag{20}$$

On the other hand, if equation 15 is derived with respect to the subjective sublevel utility, it results

$$\frac{\delta J_i}{\delta U_{local}(\boldsymbol{X})} = 0 \rightarrow U_{local}(\boldsymbol{X}) = cE_{negoz}(\boldsymbol{X}) \tag{21}$$

For both solutions, it is possible to observe that the two levels try to reach the equilibrium, varying their strategy and aiming to a compromise solution, depending on the value of collaboration constant. Once the problem has been defined, it is possible to proceed with the negotiation process depicted in Table 14.

Table 14 MONET negotiation optimization process

Multi Stakeholder Negotiation Space Exploration with Collaborative Decision making
Inputs: $stakeholder_i$ Utility functions, $stakeholder_i$ attributes, $stakeholder_i$ Collaboration constant, High level mission constraints, $stakeholder_i$ design variables and subjective constraints
Output: Set of negotiated optimal design solutions
0: Initiate negotiator optimization iteration (first guess of global design vector set)
repeat
1: Compute negotiator objectives, constraints and bid expected utility
For Each Stakeholder *i* (in parallel) **Do**
1.0: Initiate stakeholder subproblem strategy optimization (local design vector) constrained to global design
repeat
1.1: Evaluate stakeholder attributes values from analysis and simulation models
1.2: Evaluate stakeholder aggregate utility (from local and shared design vector elements)
1.3: Compute new stakeholder subproblem design point and J_i
Until Optimization *i* has converted to equilibrium (J_i ~0; stakeholder balance between collaboration/selfishness)
end for
2: compute a new negotiator subproblem design point
until 2 ->1: negotiation optimization has converted to an optimal equilibria negotiation point
exploration: Plot sensible results (e.g. pareto front if multi-objective or relative stakeholder tradespace)

Despite the collaborative optimization framework guarantees a robust solution of the final results with respect to the inter-compatibility of the involved disciplines, a post-optimality analysis, such as the Epoch-Era analysis described in [127], can be performed in order to verify the robustness of the design solutions with respect to any changes in external inputs, e.g. importance of each attribute, dollar value or socio-political aspects. Finally, the design can be competed with a final concurrent design session. Each domain expert in a concurrent design session analyses both system and mission design aspects with a more detailed design of experiment with sensitivity analysis to internal uncertainties starting from the selected negotiated design solution.

4.3.4.6 Discussion about negotiation space and its exploration

In this Section, a critical analysis of the negotiation space and possible outcomes related to its exploration will be given. An overview from knowledge development to possible hazards will be analysed.

Knowledge development and management

It results interesting that, among the several uses for negotiation space exploration, one of the most promising is the *knowledge development*. Common exploration of the impact of design choices to each stakeholder, the appreciation of the bounds of feasible design, the understanding of equilibrium within a collaborative game can be indeed explored. When well posed, the exploration can also assist systems engineers in understanding the risk and collaborative behave of stakeholders. Experts, general users, and students can play with the negotiation space exploration tool, varying utility functions and observing the effect, changing the team decisional style and exploring different outcomes and payoffs. The sensibility to design for value (or utility) can be easier to understand along with the bias given by stakeholders needs and uncertainties. An exploration of design alternatives from a negotiation point of view might give to both experts and students a new way to approach the design problem, not only from a purely technical point of view, according to the Space 4.0i era.

The concurrent development of design and enhanced collaboration

As described in [128], [129], when an objective function is used to search for design solutions, the designs that are recommended are often repugnant to the every person who constructed or informed the objective function. Generally, this dilemma results in the discovery of a mission attribute that is important but has not been included in the objective function. The multi-stakeholder development of the negotiation space and the concurrent exploration might assist in the brainstorming sessions, when each stakeholder express his/her needs, and it might avoid any loss of important attributes within the mission design. Moreover, a group exploration of design alternatives results in more stimuli towards collaborative design among stakeholders, since each one can understand the payoffs gained by the others, with proper rationales. This results is an extension of the design-by-shopping paradigm described in [130]. Here the designer explores a classic tradespace and learns what he (or she) likes while he/she learns what designs are possible. This concept can be easily extended to the negotiation space, involving also a follow up iteration to properly capture stakeholder needs.

Conceptual Design

The usual procedure of exploring a formal tradespace corresponds to build and evaluate a Pareto frontier, i.e. a set of designs in the tradespace that contain the optimal design for any possible weighting that might be assigned to the tradespace objectives in the construction of an objective function. The generation and exploration of the negotiation space pareto front allows a more rapid conceptual design with the selection of the "optimal" or "sub-optimal" design alternatives, considering all the stakeholder needs whereas speeding up the exploration of the whole tradespace. Moreover, the assistance to the brainstorming sessions might lead to unpredicted design alternatives, which in most of the case could be the most preferable ones.

Advancing the state of the art

In general, it is possible to identify three areas where negotiation space exploration might push forward the state of the art in conceptual design of modern space missions:

- Negotiation space exploration evolves the classic execution of requirements engineering, pushing towards more robust and already negotiated requirements:
    - Analysing stakeholders needs, modelling utility and game theory, allows a deeper analysis of preferences among possible designs before of, or instead of, formulating requirements.
- Negotiation space exploration offers the design team a wide range of possible designs alternatives, let the team to exploit their imagination and technical knowledge, rather than rapidly concentrating to one or three designs.
- Negotiation space explorations infuses and exploits the interrelationship among stakeholders seeing designs and forming preferences with regard to design attributes and team dynamics.

Hazards of Negotiation space Exploration

The guided exploration of the negotiation space has also several drawbacks. In particular, it is possible to underline the following ones, which consist in particular hazards, especially for untrained users.

- The Negotiation space is constrained by the limitations of the identified design vector elements during the distribution of decisional power in the design among stakeholders
  - The Negotiation space can evaluate only a small sample of the whole possible designs.
- The selection of negotiated design in the Pareto frontier still might mislead to more “nice to have” rather than “optimal” designs.
  - Multi-attribute utility might not capture the actual stakeholder needs if not well elicited.

Generally speaking, design is a human process based on creativeness. In case of new design with very low maturity, a design alternative generator cannot create totally novel ideas but rather it can assist in the generation of them. Nonetheless, it is possible to evaluate and create a new component technology roadmap, demonstrating its benefits and preference in the future through negotiation space exploration of systems exploiting the technology under analysis.

About Collaboration Constant

Currently, the elicitation of the collaboration constant has been carried out through an ad-hoc interview process, which exploited the Lottery Equivalent Probability approach. In addition, with the aim of refining the modelled result, a team behave exercise (e.g. https://goo.gl/r7L7Le) has been proposed to the stakeholders group measuring their collaboration attitude. The group exploration of the negotiation space can also be exploited to validate the modelled group dynamics. As it has been done in literature with the group exploration of trade space as suggest by Ross et.al [129], it is possible to exploit a group exploration of the trade/negotiation space in order to observe the actual response of the involved stakeholder, thus increasing the reliability of the modelled team dynamics through the collaboration constant values.

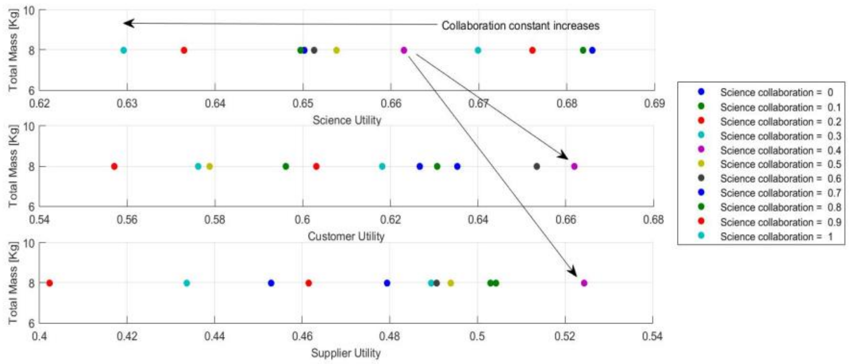

Figure 66 Influence of collaboration constant value

After the modelling of collaboration and risk behave via utility functions and collaboration constant, the next step consisted in verifying that the modelled cost function and the introduction of the collaboration constant can effectively picture the foreseen team behave. From Figure 66 it is possible to observe how the variation of the collaboration constant actually entails a variation into the final payoff (utility) from each stakeholder. According to the theoretical point of view, if the collaboration constant increases towards 1, the stakeholder is prone to collaborate reducing his/her own utility in favour of higher utility for the other parts. The redistribution of the utility is function of collaboration constant of the other stakeholders. The redistribution of utility among other stakeholders is not strictly linear, because the model is able to correctly model the dynamic among stakeholders, what value a little for one might be a valuable payoff for others (see section 4.3.3 for more details). Opposite behave is observed for decreasing collaboration constant. This evaluation assisted in the verification of the modelled group dynamics, verifying the behave of the optimizer with respect to collaboration attitude of the stakeholder.

4.3.4.7 Robustness analysis

Once that a robust design has been selected, it is necessary to talk of a system's uncertain future, or the system's ability to change or resist to external changes with respect to the design environments. Resilience of complex system is becoming more and more an important characteristic of mission design[22]. Needs uncertainties, unstable political and economic context, and technology innovation are example of scenarios in which it becomes harder for mission and systems to keep the same final utility for each stakeholder. The Epoch-Era Analysis (EEA) [127] was developed to effectively evaluate the impacts of extremal environment variations and it can be applied to the early lifecycle of space mission and systems design. EEA has been studied and applied in order to study the effects of changing contexts and needs over time on the utility of a system through the constructs and analysis of epochs and eras[127].

An epoch is a timeframe of fixed contexts and needs under which the system operates. It can be generated using a set of variables that define any factor, such as technology level, value of dollars or economical/political needs, which impacts the usage and value of the system. Any sequence of epochs constitutes an era and it pictures a potential evolution of contexts and needs over time. Any need or context, which has an impact on the mission utility or costs, can be described via definition of available epoch variables, providing a form of changing design scenario, thus allowing the ability to plan possible changing to the design and/or evaluate alternative robustness.

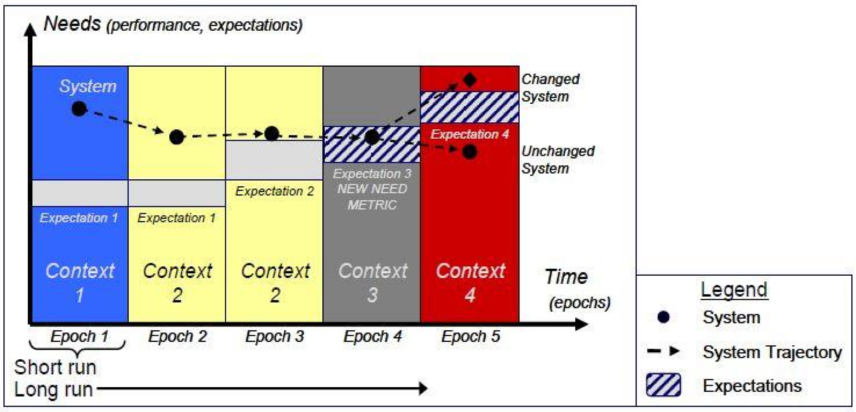

Figure 67 Trajectory of a point design during 5 epochs[127]

Figure 67 shows a notional system trajectory across an ordered sequence of epochs constituting an era. The impact of changing contexts is pictured by the system trajectory, which lower the fulfilment of stakeholder needs as the context changes over time. Lastly, in the final epoch (the 5th), the system results in a weak design. Hence, it must change in order to meet stakeholders' payoffs. In summary, EEA can give a tool to put in consideration the changing of mission contexts and stakeholders needs allowing to evaluate design robustness or suggesting strategies for how to keep the final utility over time, in both short run and the long periods.

4.3.4.8 Case Study

In this Section, the results obtained by the application of the proposed methodology are analysed. In order to verify the performance of the MONET methodology in two different group decisional scenarios, the results will be highlighted with two different implementation styles: (i) negotiation with social accepted metric (pure collaborative decision making), as the total mass to be launched; and (ii) a negotiation with customer prioritization (hierarchy group decision making style). For this problem, a genetic algorithm optimizer (see 4.3.4.4) for the negotiator and a pattern search [131], [132], one for each stakeholder, have been chosen to guide the exploration process towards negotiated optima.

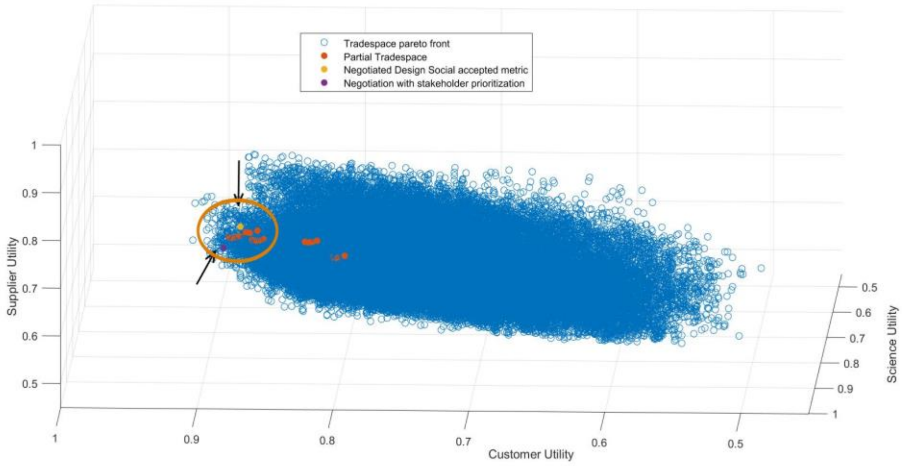

Figure 68 Negotiation Space and suggested design solution cloud

With the objective of analysing the trades and satisfaction of each stakeholder, Figure 68 shows the negotiation space, i.e. a n-dimensional space in which the stakeholders utilities are compared for each design point. From the exploration of the Negotiation Space, it is possible to observe that the negotiated solutions are located in the highest corner of the solutions cloud. This entails that the obtained negotiated results reside in the best compromise for each stakeholder. In addition, it is possible to analyse the obtained design solution with respect to the individual pareto fronts of each stakeholder. For this porpoise, a single MATE approach has been applied for each stakeholder, in order to find his/her own pareto frontier and, afterwards, the negotiated designs have been evaluated from the prospective of each stakeholder with respect to his/her own attributes and utility functions. In this sense, Figure 69 pictures the obtained results. It is possible to observe the distribution of utility obtained by changing the group decision making approach. When a prioritization is given to the customer, his/her own utility increases whereas the utility of the other stakeholders decreases, according to their collaboration constant towards the pareto equilibrium. The negotiated solutions reside in the vicinity of the stakeholder pareto frontiers but, in the case of stakeholder prioritization, it is possible to observe a switching of this scenario. Indeed, the customer prioritized solution moves closer to its pareto frontier whereas it goes farer in the case of the other stakeholders.

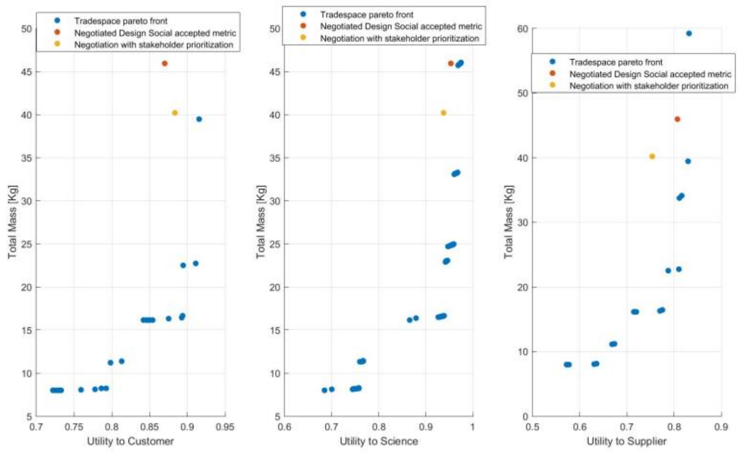

Figure 69 Negotiated design solutions with respect to stakeholder pareto front

Going into details with the negotiated design solutions, Table 15 summarize the results obtained in both the simulated decisional scenarios.

Table 15 MONET Results

Design Variable	Negotiated solution with social accepted metric	Negotiated solution with customer prioritization
Orbit Type	Elliptic	Elliptic
Elliptic Orbit periapsis altitude	150	150
Elliptic Orbit apoapsis altitude	600	600
Inclination	90	90
Right ascension of ascending node	300	270
Communication architecture	OrbiterInterlink	OrbiterInterlink
CubeSats interlink	Not Necessary	Yes
CubeSat Form Factor	8U	12U
Number of Satellites	4	2
Autonomy Level	4	4
Mission Lifetime	1	1
Total Mass to Launch	46 Kg	40 Kg
Single Stakeholder Utilities ($1^{st,}$ 2^{nd} 3^{rd})	[0.86 0.95 0.81]	[0.88 0.91 0.75]

After a detailed orbit simulation, it is possible to observe from Table 15 that key results can be summarized as follows: (i) elliptic orbit at near polar inclination, with an argument of periapsis rate capable of allowing the spacecraft to explore the lunar radiation environment at different altitudes without additional manoeuvres; (ii) absence of plane change manoeuvres; and (iii) space segment architecture takes into account high flexibility with respect to the mission effectiveness. Nonetheless in both solution the number of satellites is greater than 1, the mission could still be accomplished exploiting just one satellite but with degraded performance in terms of mission reliability and scientific return. Furthermore, it is possible to observe that among all design variables, only three of them are actual means of negotiation, whereas in both scenarios the same orbit geometry has been chosen. In the presence of customer prioritization, the number of satellites is decreased whereas the form factor is increased. This allows the optimizer to reduce the mass to launch while satisfying the needs of redundancy arising from the scientific stakeholders. The design solution in the stakeholder prioritization scenario reflects a higher utility for the powerful stakeholder and a lower mass to launch, while the needs of the other stakeholders are still satisfied. Last, it is important to notice the difference among the single stakeholder utilities in the two decisional scenarios. To reach the equilibrium and considering the same amount of decisional resources, the optimizer autonomously decided to reduce the utility of the second stakeholder whereas the utility of the most powerful one is increased. It is possible to notice that the variation of the second level stakeholder's utility is concord with the elicited collaboration constant, reflecting the concepts of distribution introduced in Figure 71, thus verifying the correct behaviour of the method. Finally, a global sensitivity analysis considering a gaussian distribution of the attribute weights (see Figure 70) has been carried out, in order to emulate the variability in stakeholder preferences with respect to different epochs with the goal of analysing the valuable changeability of the negotiated design solution.

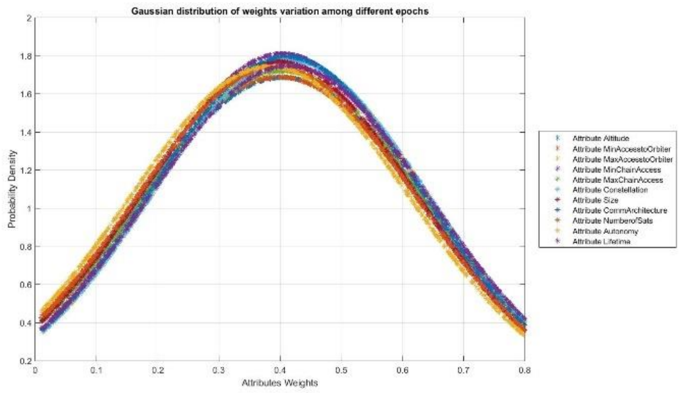

Figure 70 Weights gaussian distribution over an Era of 300 epochs

For comparison purpose, the changeability of the five most robust designs in the tradespace pareto front has been compared with the two negotiated design solutions. As it is possible to observe from Figure 71 and as expected from theoretical analysis, the negotiated designs, both with and without stakeholder prioritization, are characterized with a lower changeability over 300 epochs. This is notable by the lower area of the boxplot related to the MONET solutions.

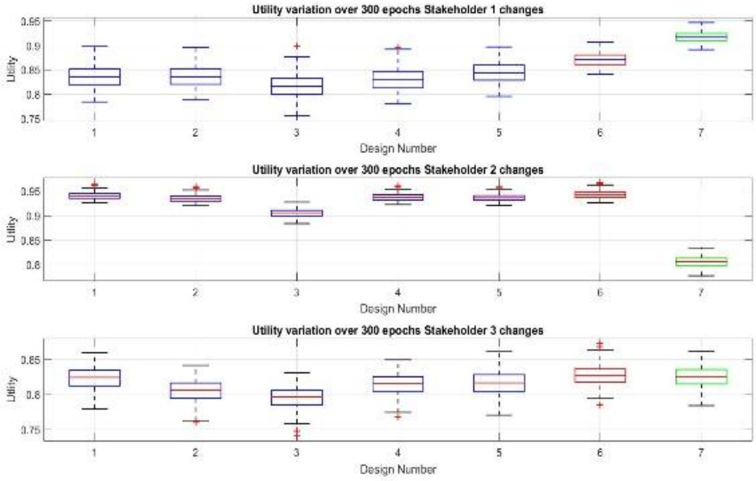

Figure 71 Utility changeability over 300 epochs (red box pictures the parity design, green box represents the negotiated design with prioritization)

Once the robust negotiated designs have been selected, expert systems could autonomously gather, store and use experts and stakeholders knowledge and preferences. With this goal, a final tool has been developed in order to obtain a broad view of the possible conceptual design of the final system. Main functions developed for the KBS and the final exploration tool can be identified as:

- *Identify*: problem and product requirements;
- *Capture*: represent and integrate product and process knowledge;
- *Enable*: knowledge reuse in generative product and process design;
- *Facilitate*: real-time collaboration across knowledge domains;
- *Support*: concurrent and group decision making;
- *Integrate*: products and processes through use of KBS.

The designed tool is infused with captured knowledge and cases from past projects, enabling its reuse, facilitating collaboration and supporting concurrent engineering.

Regarding the system architecture, Figure 72 shows the developed architecture for an autonomous design optimization and decision making.

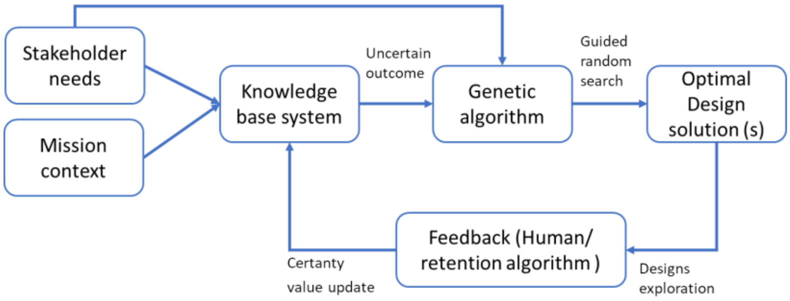

Figure 72 Knowledge based system for mission design: System Architecture

Following a goal-driven backward chaining guided search, the KBS can exclude all the rules that match with the study under analysis, providing a first solution to the design problem. When the design must be consolidated, it is important to consider all the uncertainty related to some decisions of the KBS, e.g. development time and cost, and to infuse them within the following design optimization algorithm. With the goal of managing uncertainties and constraints, the uncertain solution given by the KBS is processed by multi-objective genetic algorithm optimizer. The design iterations and relative decisions are optimized aiming to a maximization of mission utility, while minimizing a second decision metric, e.g. total mission cost. Figure 73 shows the results presented to a software user, typically the system engineer, at the end of the optimization process. Results are related to a 12U CubeSat mission with the objective of Earth observation in visible bands, and as an assumption the payload has been considered as a visible camera.

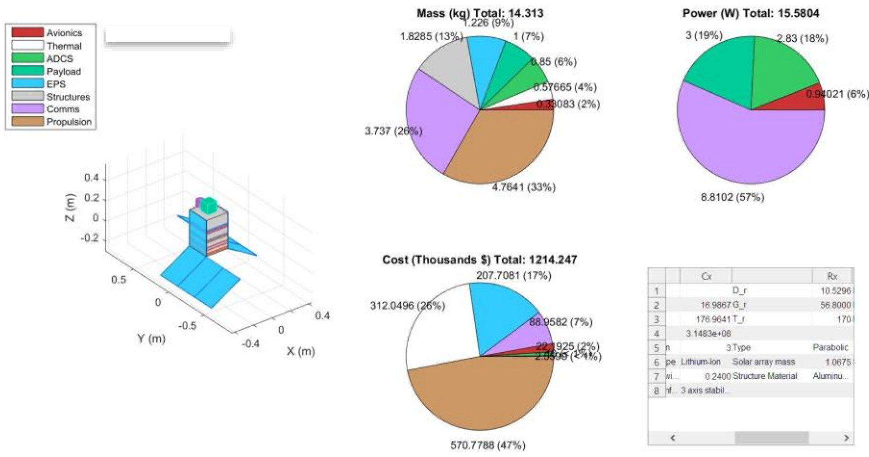

Figure 73 Output of Autonomous CubeSat Mission Design and design finalization

Then, the algorithm is able to evaluate most of the critical aspects of the conceptual and early preliminary design, from configurations to budgets, and preliminary subsystems sizing. The output of the model is visible in Figure 73, in which the system tradespace, its pareto front and the graphical user interface relative to the design finalization are provided. Going into details, in order to understand the actual decision taken by the algorithm, a snapview of the proposed system architecture is summarized in Table 16.

Table 16 Snap view of outcome from autonomous design

Subsystem	Architectural element	Value	Architectural element	Value	Architectural element	Value	Architectural element	Value
TT&C	**Eb/No**	14,0	**Modulation**	S and K band	**Antenna Type**	Parabolic		
EPS	**Cell Type**	GaAs	**Battery Type**	Lithium-Ion	**Solar Array Area** [m2]	4,4	**Regulation Type**	PPT
Structure	**Structure width** [cm]	2,8	**Structure Material**	Aluminium 7075				
Propulsion	**Propellant**	Cold Gas						
ADCS	**ADCS configuration**	3 axis stabilized-Zero momentum	**Number of RWs**	4 Tetrahedral Configuration	**Sensors**	Horizon sensor, 6 sun sensors, 2 star trackers 1 IMU		

Within the visualization of the design decision, the GUI shows the system architecture and the principal design parameters of each technical domain, waiting for a user feedback in terms of design solution acceptance or rejection. Once the user gives his/her feedback to the proposed solution, the algorithm is autonomously able to update the certainty value of each stored rule in the knowledge database, considering the final design decisions.

4.4 The MONET methodology: Assisted concurrent engineering sessions

This section covers the description of the follow-up task to the concurrent engineering study within the MONET methodology, which addresses the refinement of the selected set of design solutions via concurrent design sessions. Once a set of optimal negotiated design has been selected as preferred baseline candidates, the point designs are then employed as starting point for a set concurrent engineering session. Starting from the conceptual design and proposed architecture selected from the negotiation space, the design team is able to analyse into details their domain of expertise.

The design sessions are structured to evolve the maturity of the concept from CML 4 to CML 6 (or CML 7 depending on project complexity and study needs), handling technical uncertainties.

Following the Space 4.0i vision (see 1.4), innovative methods are integrated in the concurrent engineering sessions. Local trade space exploration, AI based expert systems, additive manufacturing and virtual reality are considered. The latter methods are able to give to the domain expert more information about the sensibility of his/her design in terms of pre-selected metrics based on mission drivers. The design sessions are managed following the agile concurrent engineering methodology presented in section 3.2.1, which considers the development of virtual prototyping and tradespace exploration. According to collaboration and communication philosophy among team members, the developed methods and tools exploited during the design sessions are aimed at fostering and encouraging communications among domain experts while keep control over the design parameters.

Next sections introduce the developed tools in order to enable these methods, highlighting benefits and possible enhancements towards future consolidated maturity in their applications.

4.4.1 Domain focused tradespace exploration assisted by expert systems

Local tradespace exploration tool has been designed with the goal of encouraging communications among team member by giving more quantitative and qualitative information about his/her discipline design.

Discipline related tradespace exploration with the support of genetic algorithm (see section 1.5) and expert systems (see 4.2) is exploited to give to the discipline expert more confidence with his/her alternatives exploration. It is

necessary to underline that within this design methodology tradepsace exploration techniques is preferred to the design of experiment (DOE) one which are advised in advanced design phases.
During design sessions discipline experts are capable of rapidly trade design alternatives against major stakeholder metrics, given by the previous concurrent engineering study.
Throughout design iterations, each domain expert is enabled to extract and employing design variables from the other domain of expertise to set-up a local tradespace exploration. This local exploration is thus constrained to the decisions taken by the other domain experts.
As an advantage, the designer is able to explore the “optimal” design alternatives faster, having a broad view of his design space against stakeholder needs. Therefore, he/she is able to negotiate his design throughout the design sessions by knowing the effects of changes in his design space to the delivered mission utility. Thanks to the application of genetic algorithms to guide the exploration process and reduced size of the problem, when compared to advanced phases of the design, complete exploration of design alternatives is carried out in around 5 to 10 minutes depending on the number of design variables considered.
The tool visible in Figure 74, is developed in Mathworks Matlab, is fully integrated in a read-write communication with Excel and OCDT.

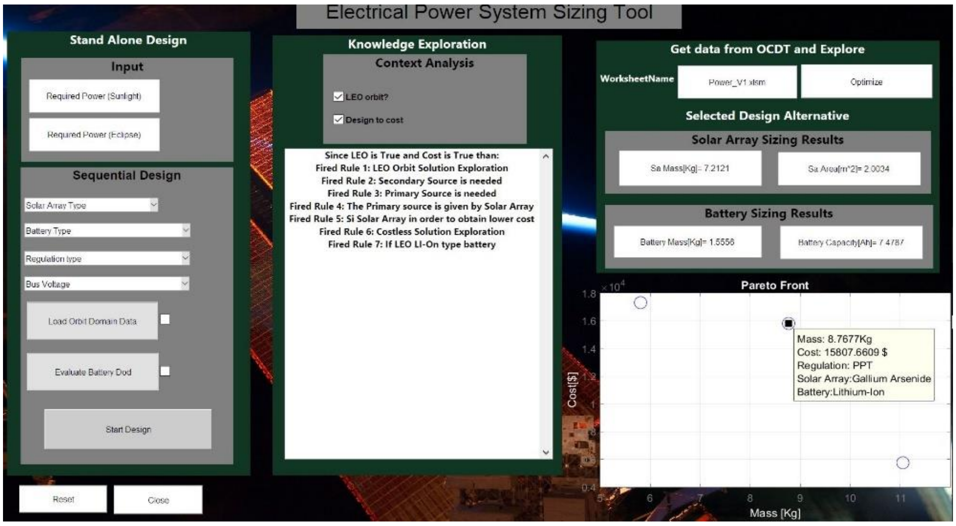

Figure 74 Domain focused tradespace exploration assisted with expert system: Graphical user interface. Discipline constrained tradesapce exploration (in the lower right side), knowledge exploration in the middle label.

Exploiting the knowledge management and utilization algorithms presented in section 4.2 and infusing the domain specific knowledge gained by experts, the tool is also able to assist the designer throughout their design process. Indeed, the expert system algorithm can fire and showing rules, in a dedicated knowledge exploration label, relative to the scenario under analysis, thanks to the knowledge gathered from experts and literature according to available design data and mission context.

The main goal of this function is to guarantee a tracking of design variable exploiting autonomously designer experiences and/or state of the art. In addition, the design assistant keeps under control expert design, knowing in details tips and procedures to properly design their domain. This avoids any missing step or wrong design parameters.

The application of this integrated tools within a Concurrent Engineering Facility, results in a more performing design sessions, efficiently assisting domain experts throughout their design tasks.

4.4.2 Autonomous virtual reality generation and 3D printing within CE sessions

Humans are highly visual creatures, and the field of visual analytics has recently developed around the topic of assisting human-in-the-loop analysis and design for both learning and decision making [133].

Visual analytics has been applied in design and modeling, to assist designers when approaching complex systems with large amounts of multi-dimensional data [134]. Visual analytics have potential value for this research, as the system design process is a data-intensive process and is driven by visualizations of that data that create information. Incorporating real time visualization of the design iteration has also the potential to increase stakeholders' satisfaction to the design outcome. This is obtained by better illustrating the benefits of the design solution puzzling out the "black box" nature of complex systems.

The main concepts of the visual analytics paradigm are: analyze first, show the important, zoom/filter and analyze further, and details on demand [135]. Specifically, they are:

- Analyze first: reduce stresses on human by performing analysis in the background;
- Show the important: direct attention to the most critical information;

- Zoom/filter and analyze further: iterative design evolution with gradually increasing detail;
- Details on demand: when requested, revealing the details that was originally hidden to reduce complexity.

Incorporating these concepts in the system design process can assist both learning and negotiation goals by reducing complexity and directing attention to effective areas of the design alternatives. Virtual Reality (VR) technologies fits these concepts efficiently.

With the objective of verify the effectiveness of VR within CE studies, a dedicated tool was developed within this research. To develop the introduced tool, two VR solution have been analysed. The Virtual Environment Research in Thales Alenia Space (VERITAS) and the open source Blender®. To reduce the effort required from the experts, an autonomous generation and management of a VR environment has been developed as proposed by Casini et. al. [136].

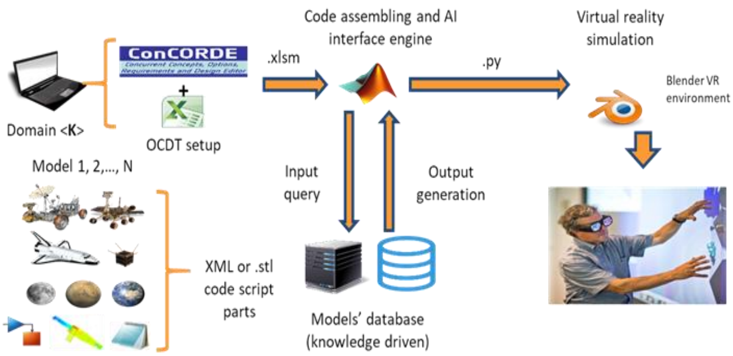

Figure 75 Autonomous VR generation architecture using Blender®

Figure 75 shows the architecture of the tool developed for the integration of Expert systems within the design process, via ESA's ConCORDE suite.

A expert system developed in MathWorks MATLAB is employed to generate and manage the VR environment exploiting a structured database containing both sample 3D model and modelling knowledge. The ES can update the simulation model in quasi real-time (the computational cost is the main constrain) based on the OCDT design data, giving to the designers an immediate feedback and offering a first verification loop of their design.

This implies an iterative verification and optimization in the deductive branch of the classical system engineering V-model, yet in the deductive phases (see Figure 76).

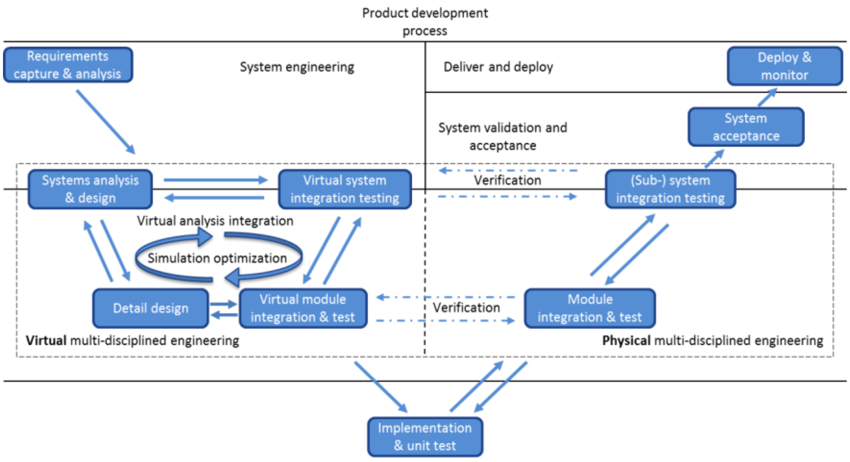

Figure 76 The development process with the integration of VR

To test the functionality of the developed virtual reality environment, the LRO mission has been virtually recreated using Blender®. Starting from the data gathered from a mission analysis calculation sheets, the celestial bodies (i.e. Earth and Moon) have been imported from the internal knowledge database, where all the planets of the Solar System are present, and a CAD model has been used for LRO visualization [137]. Position of the planets has been defined using a geocentric reference frame with ephemeris. Orbits and attitude of the spacecraft has been defined by its mission orbital parameters, evaluated and extracted from the calculation sheet.

A python script has been compiled and a blender internal tool has been used as render engine, speeding up the scene creation. The code gives in output the visualization of spacecraft trajectories into the Solar System, with all the planets moving correctly thanks to ephemeris evaluation.

As result, it has been possible to customize the view point of the scenario as in Figure 77 and Figure 78.

Figure 77 Earth and Moon in the first point of view autogenerated scenario

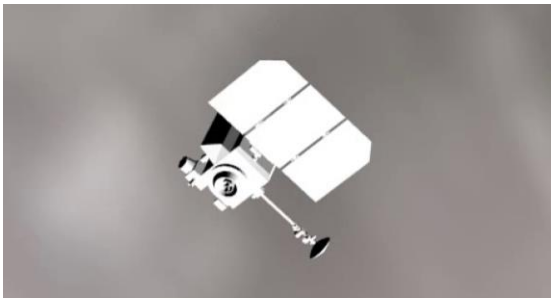

Figure 78 LRO orbiting over the Moon: autogenerated scenario

The very simple case study proves the feasibility of the proposed algorithm.

In addition, the case study described in Section 3.6 has been analysed using both a proprietary ad-hoc solution and an open-source multi-purpose software for benchmarking pros and cons of each approach, observing the expertise level required for the potential end-users of a CE-VR solution. Future test cases are foreseen to iterate and enhance the current infrastructure.

In parallel to virtual reality, rapid prototyping technologies may experience significant growth by the broad introduction of 3D printing technology as suggest by Stjepandić et.al. [17]. The rising variety of used materials with improved technical properties opens entirely new options for rapid and low-cost production of mock-ups.

According to the agile concurrent engineering methodology presented in Section 3, a Fused Deposition Model technique with Polylactic Acid material has been selected to rapidly print the conceptual model of the system. An example of a 3 Unit CubeSat designed and printed during a four days concurrent engineering session is shown in Figure 79. In the case of CubeSats systems, pre-printed structural and architectural elements are considered in order to speed up the prototype integration process.

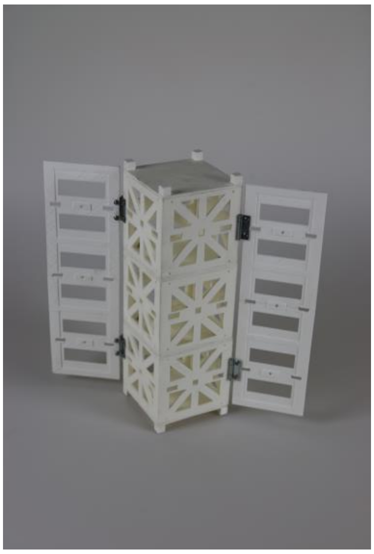

Figure 79 3D printed PLA 3U CubeSat: structure prototype

The prototyping approach within the design methodologies developed in this research shows promising results, assisting the decision-making processes thanks to strategies based on visual analytics theory. Learning opportunities are enhanced as well. Visualizing the design, understanding possible issues and increasing the quality are important aspects that are enabled with virtual prototyping approach. It is straight forward that, as for the knowledge management which requires a knowledge engineer within the design team, a prototyping engineer will be required in order to effectively manage the development of the mock-up(s).

Finally, a closed-loop in the mutual interoperability between virtual and physical products using rapid prototyping can not only increase the quality of the final baseline but also the learning opportunities. A full functional integration between the two prototyping models is foreseen in the next future.

Chapter 5

Conclusions and recommendations

5.1 Major findings

Concurrent engineering has been and still is a promising design approach in the context of both industrial and academic applications. The emerging trends of innovation and involvement within space-related activities are pushing this design approach as primary preference towards designing space missions in the Space 4.0i era.

The opportunity of educating future engineers via the application of the Concurrent Engineering (CE) approach has been investigated and a tailored design methodology has been developed, with a successful application to the case study proposed within the first ESA academy CE challenge. The studied design approach is built around a proto-spiral design model infused with the standardization of design sessions by JPL's Concept Maturity Level. The design methodology resulted suitable in response to future teaching needs and projects effectiveness. Employing a structured design approach with the application of modern collaborative tools, e.g. Trello®, and assisting the decision-making processes through the development of virtual and 3D printed prototypes led to increase not only the learning experience but also the delivered quality of the project.

Once proven the effectiveness of CE for educational porpoise, the research focused on the study of an innovative design methodology able to enhance the benefits given by the CE approach. As a result, it has been highlighted how the incorporation of game theory, collaborative optimization and

Multi-Attribute Utility Theory (MAUT) can assist the modelling of negotiation dynamics among stakeholders, thus reducing the number of design iterations and engineering effort.

The developed methodology, named Multi-stakehOlder Negotiation space ExploraTion (MONET), ensures inter-compatibility and satisfaction among stakeholders while guaranteeing the technical feasibility of the selected design solution. The proposed methodology allows the decision makers to manage and to understand effectively the negotiations among stakeholders, either internal or external to the project, thanks to a structured exploration of the negotiation space. The collaborative optimization framework guarantees the introduction of stakeholder subjective design constraints, guaranteeing inter-stakeholder compatibility and avoiding the violation of the Arrow paradox, since each stakeholder is free to manage his/her own preferences and an inter-comparison of subjective utility is not introduced.

The proposed optimized negotiation process is carried out via genetic algorithm at negotiator level and via pattern search at sublevel, speeding up the entire exploration process. This choice guarantees a global optimization even with discontinuous functions, faster exploration process and avoids optimizer convergence problems, which can be an issue for the collaborative optimization framework. Furthermore, thanks to the adoption of MAUT and estimated expected utility, MONET has integrated an algebraic approach to aggregate single stakeholder preferences and to simulate a collaborative game, aiming to a social accepted design result. This methodology provides to systems engineers a metric to evaluate several system design options from a negotiation point of view, improving the effectiveness and social utility of the design solution. It also attempts to quantify and to better understand stakeholder preferences and collaboration behave, thanks to the measure of a collaboration value, measurable via lottery equivalent probability methods. The collaborative exploration of the negotiation space reduces the likelihood of wrong communications in the later stage of the system design process, allowing to derive robust requirements later in the design phase.

In the case of more than three stakeholders, a parallel computing approach is advised due to the excessive computational time. Nonetheless, this constraint is not critical since the methodology has been developed for an integration within a Concurrent Design Facility, in which advance information technology techniques are applied. Last, an additional integration of multi-stakeholder Epoch-Era Analysis can explore the robustness and the value changeability of the negotiated design with respect to changes of context and needs in the external design environment, providing a useful method to guarantee the goodness of the design solution. Moreover, the proposed methodology results suitable to handle multi-stakeholder problems at system level and, at the state-of-the-art, provides support to the engineering team in the decision-making process, with inclusion of: (i) novel technologies, such as Artificial Intelligence-based techniques, and methods, e.g. Multi-Disciplinary Optimization for tradespace exploration, integrated into a single environment; (ii) value-oriented design via application of MAUT and advanced group decision making techniques; (iii) standardisation of design session objectives and execution; and (iv) integration of prototyping approach, both virtual and 3D printed. To conclude, the developed methodology results suitable to handle multi-objective problems at system level and, at the state-of-the-art, MONET provides benefits that will assist and great improvements in handling negotiation problems in system design.

5.2 Comparison with state-of-the-art methodologies for tradespace exploration

In order to validate and verify the goodness of the proposed design methodology, the negotiated design solutions have been compared with the topology of the problem Tradespace and with the pareto frontier evaluated with multi-objective genetic algorithm applied in a Multi-Attribute Tradespace exploration problem. Among about 6 billion of design alternatives, Figure 80 shows a partial Tradespace with 100000 designs over the total of 6 billion.

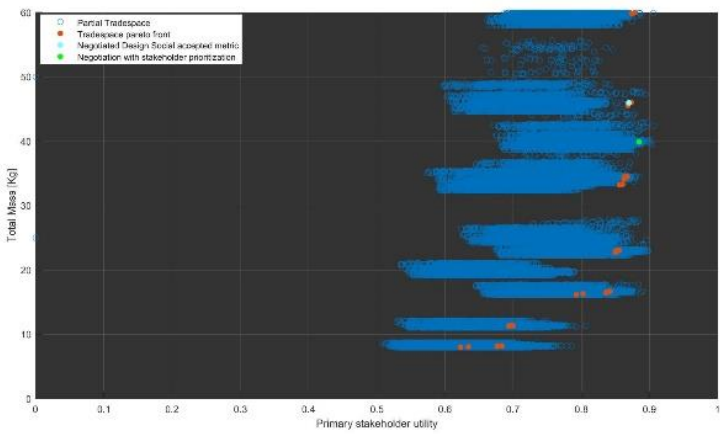

Figure 80 Partial MATE Tradespace, pareto front and negotiated design solutions are highlighted

When in the tradespace are highlighted only the pareto front and the negotiated design points, it is possible to observe that the negotiated solutions reside near the pareto frontier but are identified by unexplored design solutions by the genetic algorithm applied with the nominal MATE formulation. Moreover, the MONET design solutions picture the trend of the modelled decision scenario via the value of customer utility (i.e. higher for the stakeholder prioritization case). Hence, the negotiated solutions are still optimal or sub-optimal for the customer but considers also the needs of the other group members.

The application of negotiation and TSE analysis to engineering problems requires the implementation of an explorer that navigates the solution space and depending on the dimension of the problem and the explorer design, obtaining the Pareto front can be expensive, both from a computational cost and time perspective.

Table 17 - Algorithm performance comparison

Algorithm	Problem Size Considered	Time Complexity	Average Execution Time	Pareto Front Found
Monte Carlo	$8*10^{16}$	O(N*f)	Undefined	No
MONET	$8*10^{16}$	O(n*G*f)	1 hour	Yes
Non-Guided Exploration	$8*10^{16}$	O(N*f)	$1.8*10^{10}$ hours	Yes
CD	Inherently smaller	-	2-4 weeks	No

Table 17 presents a comparison with other methods used to explore a tradespace. The algorithms explored are: Monte Carlo method, GA, Non-Guided exploration (where every single solution of the tradespace is evaluated) and CD. The CD approach is reported for additional comparison with traditional methodologies for space mission preliminary design. The tradespace size is also presented to offer a comprehensive view of the comparison. For CD sessions, the solution space defined by experts is smaller than the one implemented on a computer simulation: considered solutions are biased towards previous experience, preferences of the experts, adversity towards innovation and bias towards safer solutions. Moreover, not only the generation of a proper tradespace is challenging for a human expert, but this space will be biased towards the preferences of the expert himself, instead of reflecting the stakeholders' goals. Time Complexity column describes the complexity of the algorithm from an execution time perspective, using the common Big O representation. N represents the solution space size, f the complexity of the fitness function, n the max number of generations for the GA, and G the GA population size.

5.3 Final Thoughts and future works with recommendations

I would like to begin this section with three quotes which might summarize my personal research experience. In chronological order:

The moments of initial confusion:

"Research is what I'm doing when I don't know what I'm doing."
Wernher von Braun

The moment of understanding:
"Research is creating new knowledge."
Neil Armstrong

The moment of resignation:
"The more original a discovery, the more obvious it seems afterwards."
Arthur Koestler

This research has been developed with two goals in mind: 1) extending the applications of TSE to multi-stakeholder problems exploiting and adapting novel optimization and negotiation methods 2) increasing the effectiveness of the concurrent engineering approach and adapt it in an academic environment, enhancing the learning approach and preparing future engineers to their future jobs since as Malcom X stated:

"Education is the passport to the future, for tomorrow belongs to those who prepare for it today."
Malcom X

It is our belief that the two developed methodologies, MONET and Agile CE, are able to give a valuable process and methods to systems engineers by 1) understanding of negotiation processes and exploration of value changeability in a multi stakeholder point of view 2) preparing future systems engineers to their future jobs 3) structuring stakeholders, their needs and design team management yet in the initial design phases. The feedback that has been received both from within this research and from without (conferences and workshops, current active research worldwide) has been positive. We are confident that this research is addressing a silent need which is day by day becoming more important, moving our ability to handle multi-stakeholder engineering systems. MONET has still many developments ahead of it, in particular the following topics are foreseen to be further analysed:

- Intensive research on collaboration constant elicitation and interaction with interactive negotiation space exploration
- Increasing knowledge infusion with AI algorithms and follow-up benefits analysis
- Detailed analysis of knowledge extraction and acquisition, such as with natural language processing algorithm , might increase the knowledge management process with AI algorithm
- Additional case studies might be needed to increase the confidence with the new developed methodologies
- Detailed analysis about the optimization process would be beneficial to increase the effectiveness with the algorithm
- The analysis of methods to increase connection with SysML and MBSE tools would be beneficial to harmonically extend MONET to advanced design phases
- The maturity and the future enhancement of autonomous virtual reality and additive manufacturing for prototyping in order to increase its effectiveness within the design methodology and the design team

To conclude, we hope that this research has investigated a set of interesting research topics increasing the knowledge related to them. We are excited to see what the future will bring.

Glossary

- **Negotiation Space**: A multi-variant mathematical playspace used for identifying the optimal boundary design spaces (i.e. Nash or Pareto frontier)
- **Data**. Individual measurement or design data, by themselves, are simply numbers, and therefore represent data.
- **Information.** Information on the context of the mission. This information can be used by someone to make a decision.
- **Knowledge:** Knowing the context and the nature of the mission derive how to design, how to use the design data and which decision take during the system lifecycle.
- **Knowledge Based Systems**: An artificial intelligence algorithm composed by uncertain rules able to interface with the context in order to take autonomous decisions and learn from errors
- **Game theory**: mathematical approach to analyse situation in which choices made by one decision maker affect the objectives and strategy of other decision makers and vice-versa, it helps in the set-up of the optimization architecture.
- **Collaborative**: Decision makers with different goals and values merge their effort for a unique high-level goal as the benefit of the whole team.
- **Collaborative optimization**: A bilevel optimization architecture able to guarantee parallel computing, single discipline feasibility and interdisciplinary compatibility
- **Subjective Utility**: The subjective value of a decision outcome, it includes all the uncertainties related to non-rational decisions where uncomplete information are given.
- **Expected Subjective Utility**: a tool which aims to foreseen the subjective utility that comes from a particular choice

Appendix
A: Space program life cycle and phases

In this section the principal phases composing the lifecycle of a space mission will be briefly described with particular attention to goals and reviews which characterize the phase itself.

Phase 0: Stakeholders Needs and Mission Analysis

- **Goal**: Analysis of involved stakeholder needs and mission drivers to identify and characterize the planned mission goals and preliminary conceptual design.
- **Review**: Mission definition review (MDR)

Phase A: Feasibility analysis

- **Goal**: Finalization of the mission characteristics and conceptual evaluation of alternatives and associated conditions and utilities, compilation of different system concepts, finalization of the high and medium level functional requirements.
- **Review**: Preliminary requirements review (PRR)

While typically Phase 0 and Phase A studies are performed by agencies and institutions, the follow-up Phase B usually is carried out by the main or sub-contractors which are identified by the customer.

Phase B: Preliminary Definition Phase

- **Goal part 1**: Preliminary definition of the mission with selection of possible technology in order to fulfil the requirements identified for the system concept chosen in the PRR.
- **Review**: System requirements review (SRR)

- **Goal part 2**: follow up detailing of technical solutions concerning detailed selection and definition of methods, resources and products with evaluation of effort (e.g. man hours) and implementation planning.
- **Review**: Preliminary definition review (PDR)

Based on the interim results of Phase B as confirmed by the SRR, the contractor and sub-contractors will be in charge to perform the follow-up phases.

Phase C: Detailed Definition Phase

- **Goal**: Detailed exploration of the selected technical solution concerning manufacturing solutions and qualification approach of representative elements, validation of technical and programmatic feasibility and fulfilment of requirements.
- **Review**: Critical design review (CDR)

Phase D: Production Phase or MAIT Phase (Manufacturing, Assembly, Integration, Testing)

- **Goal phase 1**: Procurement of components, manufacturing of first models according to identified model philosophy with the aim of qualification of the selected point design, verification of manufacturing methods and operational procedures.
- **Review**: Qualification review (QR)
- **Goal phase 2**: Manufacturing of flight models with respect of qualification test results, verification of reliable manufacturing outcomes, validation of functional performance and operations, availability for transportation to the launch site.
- **Review**: Acceptance review (AR)

During these phases is possible to have a consolidated overlap of the standard sequential phases. Indeed, the procurement process and the component development begin in Phase C. The outcomes of qualification related to already available component level can be reviewed yet at CDRs.

Phase E: Operations (Launch and Early Operation Phase and in-orbit operation phase:

- **Goal part 1**: On ground evidence of functional performance of the overall system (satellite and ground segment), mission readiness validation.
- **Review**: Operational readiness review (ORR)
- **Goal part 2**: Preparation and execution of the launch campaign, release for launch.
- **Review**: Flight readiness review (FRR), Launch Readiness Review (LRR)
- **Goal part 3**: Commissioning of satellite and overall system, operation and use.
- **Review**: Commissioning Results Review (CRR)

Phase F Disposal Phase

- **Goal**: Conclusion of the end of life performance, system deactivation.
- **Review**: End of life Review (ELR), Decommissioning Review (DR), Mission Close-out Review (MCR)

B: Project development indexes-Concept Maturity Level (CML)

When dealing with space mission conceptual design, especially in the context of preparing a proposal to be presented to a space agency, one metric to describe the level of details can be found in the NASA JPL Concept Maturity Level (CML). The CML has been inspired by the Technology Readiness Level (TRL) already been part of the state of the art within the aerospace industry. A description of the Concept Maturity Levels, with a case on a scientific mission is given in Table 18. This metric aims at giving a value to both the maturity of the science planning as well as its engineering design.

Table 18 Concept Maturity Level description scientific mission case [60]

Level	Science	Detailed description	Engineering	Detailed description
1	Science Goals	What does the mission intend to accomplish?	High-level Description	What mission is envisioned?
2	Top-level Science Objectives	Quantify objectives in order to allow validation of physical feasibility	High-level Comparison to Similar System	To assess flight system feasibility, identify new developments and key performance parameters
3	Prioritized Objectives; Investigations	Explore multiple architectures for achieving objectives; evaluate science value, mission cost bin, mission risk for each architecture	Alternate Architectures	Evaluate system design in response to alternative architecture
4	Baseline & Threshold Mission Attributes; Science Traceability Matrix	Document selected design: Traceability matrix (science, to instruments, to data products, to key mission features); baseline and threshold mission attributes	System & Subsystem Block Diagrams; Configuration & CAD Drawings	Establish initial flight system design
5	Concept Baseline Science Requirements	Detailed Traceability Matrix will all top-level science requirements (mission drivers) identified	Document Design	Enable external evaluators and costing
6/7	Initial Design; Level 2 & 3 Science Requirements		Preliminary Systems & Subsystem Design	Prepare for implementation

C: Agile Project management Manifesto

The Agile Manifesto follows these 12 principles that inform and reinforce the manifesto:

- The highest priority is to satisfy the customer through early and continuous delivery of valuable product.
- Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.
- Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale.
- Business people and developers must work together daily throughout the project.
- Build projects around motivated individuals. Give them the environment and support they need and trust them to get the job done.
- The most efficient and effective method of conveying information to and within a development team is face-to-face conversation.
- Working product is the primary measure of progress.
- Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely.
- Continuous attention to technical excellence and good design enhances agility.
- Simplicity (the art of maximizing the amount of work not done) is essential.
- The best architectures, requirements, and designs emerge from self-organizing teams.
- At regular intervals, the team reflects on how to become more effective and then tunes and adjusts its behavior accordingly.

D: Politenico di Torino Concurrent engineering facility: calculation sheets

With the goal of enabling different discipline evaluations the calculation sheets highlighted in Table 19 have been developed. In particular, dedicated features are indicated for each calculation sheet. The models implemented in the calculation sheets refers to Wertz et. al. [138], Larson et.al. [71], [139].

Table 19 Politecnico di Torino Calculation Sheets

Calculation sheet	Features
Telecommunication Payload	Dedicated calculation sheets for telecommunication payloads with different operational bands
Operations complexity	Evaluation of complexity related to mission operations and estimation of operators FTEs, number of ground operators
Ground Segment Design	Sizing and estimation of ground segment power, antennas characteristics and definition of system architecture elements
Cost Budget	Evaluation of mission costs based on SSCM and USCM cost models. Estimation of costs related to the whole mission life cycle.
Data Handling System	Definition of subsystem architecture, data budget, on-board software size and board frequency/ throughput
Mission Analysis	• Mission timeline • Orbit dynamics, geometry and manoeuvres • Interplanetary mission analysis

	• Visualization of satellite coverage with respect to planet latitude • Patch conic approximation for interplanetary transfer • Launch windows evaluation • Interplanetary mission database • Fly-by evaluation • Launch sites information • Earth observation mission database • Vega 6 within launchers database
Attitude Determination and Control System	• Evaluation and visualization of external disturbances through one orbit period (trapezoidal integration) • Estimation of proportional control tuning and control bandwidth • Selection of spacecraft material for optical proprieties (solar torque) • Actuator summary panel • More detailed equipment characterization (i.e. thrusters misalignment, dry mass)
Communication Subsystem (with and without Ground Segment Expert)	• Uplink and Downlink evaluation • Interlink evaluation • ESA ground systems database • Evaluation of design alternatives with respect to link margin capabilities (i.e. transmitter power, antenna diameter) • Definition of link typology for link margin evaluation (data dump, flight termination, command and control) • Type of modulation of probability of error estimation • Goal seek macros for closing link budget varying satellite altitude and antenna beam width
Optical Payload	• Earth observation payload database • Earth observation mission database

	• Multi spectral instrument design • Along track formation and stereoscopy design • Optics design • Payload sizing from analogy
Power Subsystem	• Power budget from OCDT data • Manual power budget evaluation with respect to subsystem peak power and/or operative modes • Primary and secondary source sizing • Solar cell technology selection • Added bus regulation type for transmission efficiency • Evaluation of number of cells in parallel and series (plus total number of cells) in the array • Evaluation of battery energy transient and power dissipation • Lithium battery dod vs life cycle graph
Propulsion Subsystem	Chemical and electrical propulsion sizing Interactive plots for fast alternative exploration (e.g. variation of Isp, spacecraft mass, delta V)
Thermal Subsystem	• Added thermal budget (manual and from OCDT) evaluation for estimation of maximum and minimum operating temperature • Passive thermal control design • Solar panels thermal analysis • Updated spacecraft surface finishes type • Introduced spacecraft structure for evaluation of specific heat capacity • Selection of solar flux intensity • Interactive exploration of passive thermal control design alternatives

	• Evaluation of temperature decreases during eclipse times
Structures	• Prim shape with monocoque and semi-monocoque models • Static and dynamic analysis • Updated structure materials databases

E: Technology Reediness Level (TRL)

The Technology Readiness Level (TRL) scale was developed in the 1970-80's by the National Aeronautics and Space Administration (NASA). The main rationale was to introduce this scale as a discipline-independent, program figure of merit to allow more effective assessment of the maturity of new technologies.

The TRL scale was developed to allow standardized assessment of the maturity of a technology, enabling the comparison of different technology.

Table 20 Tecnology readiness level

TRL level	Description
TRL 1 Basic principles observed and reported	Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are Mathematical formulations or algorithms.
TRL 2 Technology concept and/or application formulated	Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the appli-

	cation are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3 Analytical and experimental critical function and/or characteristic proof-of concept	Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
TRL 4 Component/subsystem validation in laboratory environment:	Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
TRL 5 System/subsystem/component validation in relevant environment	Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)	Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
TRL 7 System prototyping demonstration in an operational environment (ground or space)	System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)	End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space	Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

F: Fuzzy reasoning: combining certainty factors

For a hypothesis H and an evidence E is possible to derive the combination given by uncertain rules modelled by certainty factor methods as function of the propositional logic behind the combination of the rules[87]. In specific:

Multiple Rules Providing Evidence for the Same Conclusion

There are situations when multiple sources of evidence produce CFs for the same fact.

For instance, two (or more) rules may provide evidence for the same conclusion:

IF E1

THEN H {CF=0.5}

IF E2

THEN H {CF=0.6}

In such situations we need to combine the CFs. If two rules both support the same hypothesis, then that should increase our belief in the hypothesis.

The combination of the CFs is given by the formula:

$$CF(H, E1 \wedge E2) = \begin{cases} CF(E1) + CF(E2)(1 - CF(E1)), if\ CF(E1), CF(E2) > 0 \\ CF(E1) + CF(E2)(1 + CF(E1)), if\ CF(E1), CF(E2) < 0 \\ \dfrac{CF(E1) + CF(E2)}{1 - \min\{|CF(E1)|, |CF(E2)|\}}, if\ sign(CF(E1)) \neq sing(CF(E2)) \end{cases} \quad (22)$$

Multiple Rules with Uncertain Evidence for the Same Conclusion

In the previous case, we saw that if the evidence E is observed, then we can conclude H with a CF. However, there are situations where the evidence E itself is uncertain.

For instance, in the rule:

IF E

THEN H {CF=0.5}

evidence E also has a certainty factor associated, say 0.9 (we are not 100% sure about this evidence).

Evidence may also be uncertain when it itself is gained from applying a rule:

Rule 1:

IF A

THEN B {CF=0.4}

Rule 2:

IF B

THEN C {CF=0.3}

So, when we go to apply the second rule, we need to take into account that the premise is not certain.

Rule with Uncertain Evidence: One Premise

When a rule has a single premise, the certainty of the conclusion is the product of the certainty of the premise multiplied by the certainty of the rule:

Rule 1:

IF A

THEN B {CF=0.4}

Rule 2:

IF B

THEN C {CF=0.3}

CF(C) = CF(B) * CF(Rule 1)

If the CF of A is true is 0.9 then:

CF(B) = CF(A)*CF(Rule 1) = 0.9*0.4 = 0.36

and

CF(C) = CF(B)*CF(Rule 2) = 0.36*0.3 = 0.108

Rule with Uncertain Evidence: Negative Evidence

A rule is only applicable if one believes the premise to be true. If the CF of the premises is negative (one does not believe them) then the rule does not apply.

IF E

THEN H {CF=0.6}

But, if CF(E)=-0.2, then we cannot say anything about E being true.

Thus:

$$CF(H) = \begin{cases} CF(E)CF(Rule), if\ CF(E) > 0 \\ 0, otherwise \end{cases} \tag{23}$$

A value of 0 for CF indicates that we know nothing as the result of applying the rule (we neither believe nor disbelieve). Thus, our knowledge does not change.

Rule with Uncertain Evidence: Multiple Premises

If the rule has multiple premises joined by ***AND***:

IF E1

AND E2

.

.

AND En

THEN H {CF}

then CF(H) is calculated as:

$$CF(H) = \begin{cases} \min\{CF(E1), \ldots., CF(E_n)\}, \quad if\ CF(E_i) > 0, i = 1,2, \ldots., n \\ 0, otherwise \end{cases} \tag{24}$$

If the CF of any one premise is ≤ 0 then the CF of the set is ≤ 0 and the rule does not apply. Thus, when evaluating the premises of a rule, one can stop processing if a premise has CF ≤ 0.

If the rule has multiple premises joined by ***OR***:

IF E1

OR E2

.....

OR E_n

THEN H {CF}

then CF(H) is calculated as:

$$CF(H) = \max\{CF(E1), \ldots., CF(E_n)\} * CF(Rule) \tag{25}$$

G: Science Traceability Matrix

An innovative tool which is currently being used in all NASA science mission proposals is the Science Traceability Matrix (STM). The goal of the STM is to correlate measurements and data collection of a science mission to the mission requirements, scientific questions and mission objectives.

The structure of a Science Traceability Matrix is shown in Figure 81.

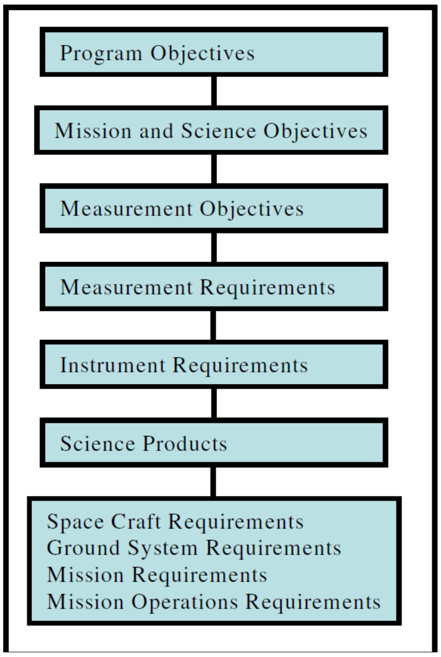

Figure 81 Science Traceability Matrix structure

[101]The STM can inform how trade studies should be conducted, and it gives guidance on how to properly analyze mission's effectiveness. Additionally, it indicates the flow of engineering requirements from the instrument level to, in case it is necessary, the spacecraft subsystem level. The effects different instrument approaches can be seen on the overall science value of a mission and the engineering requirements and design of a mission. An example STM is shown in Figure 82.

NASA Solar System Exploration Roadmap	***Objective #1:*** Learn How the Sun's Family of planets and minor bodies originated ***Objective #2:*** Determine how the solar system evolved to its current diverse state
Mission Objectives	To determine the state, atmosphere and structure of "Planet" and the structures of it's satellites

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements	Data Products
Planet					
2. Internal structure	measure gravity field	Gravity moment to order 12	Radio	3 bands to recover propogation	gravity moment of order n (n~ 12)
	measure magnetic field	Magnetic moment to order 14	Vector Magnetometer	Resolution 0.1 nT, mounting orientation to 10 arcsec	magnetic moment of order n (n~14)
3. Magnetosphere structure, plasma dynamics and radiation belts	measure magnetic field, charged particle and plasma waves over a large range of lattitudes, longitudes, and altitudes, and local time (need to rotate the line of apsides 180o)	Field direction to 1 degree, field resolution 0.1 nT, continuity 95%	magnetometer, plasma, low energy protons (LEP)		magnetosphere map, plasma spectrum, proton spectrum
Satellites					
1. Characterization interior, surface structure, activity and atmosphere.	multispectral IR imaging of surface	Map full surface at 3 meters/pixel	Mapping IR spectrometer	SNR 30, ifov 0.5 mrad, FOV 8.5 degrees	high resolution global coverage multispectral image data
	measure gravity field	circular orbit, global coverage for > 3 rotations, order 6	radio science		gravity field map
	measure magnetic field	circular orbit, global coverage for > 3 rotations	magnetometer	0.5 nT resolution	magnetic field map
	measure surface topography	100m track spacing	laser altimeter	30 meter spot size, 10 hz pulse, 1 nanosec gates	topography map

Figure 82 Science traceability matrix an example[101]

G.1: Lunar CubeSat case study: Science Traceability Matrix

Science Needs/Questions	Science Objectives	Science Requirements	Measurements Requirements	Instruments	Instrument requirements	Mission Requirements	Data Products
What is the radiation load in the vicinity of the Moon and how can we characterize it in preparation for future human exploration missions including long term extended stays at the surface of the Moon?	Characterize the radiation environment in the vicinity of the Moon as function of the solar activity and seasonal variations.	Measure the constituents of the space radiation field, namely the Galactic Cosmic Rays (GCR) and Solar Particle Events	• Measure the energy deposition range from 0.06 MeV to over 200 MeV • Determine the Linear Energy Transfer spectra (LET spectra) in the region from 0.1 to a few hundred keV/µm. • Measure the dose equivalent based on the absorbed dose and LET spectra measurements.	Radiation detector	• Mass around 300 g • Volume: 9 x 9 x 9 cm3 (to be fitted within 1U) • Electronics: Input Voltage +9 - +36V • Power: Max 2.5W • Data interface: RS-485 / RS-232c • Thermal: Operational -20°C to +40°C , Storage: -80°C to 100°C (for	• Lunar orbit with Polar or high inclination • Increased /decreased orbit altitude for the determination of changes in albedo particle flux • Spend a relevant amount of time in the lunar orbit for the determination of the influence of the sun activity on	• Radiation map with a coverage of 75% or higher • Correlation of radiation data with orbital parameters (3D Map)
		Measure the constituents of the space radiation field, including possible albedo particles from interaction of					Time resolved count rates (1-minute resolution)

		the main radiation field with the surface of the Moon.	• Operate continuously over the mission duration and acquire data with a time resolution < 5 mins • Energy resolution better or equal to 40 energy bins per decade (dynamics = 4 decades).		lower operational temperatures heating would be required) • Vacuum: Detector works under vacuum conditions • FOV: Pointing direction Zenith (accuracy +/- 10°) • Resistant to strong Solar Particle Events • Produce < 5Mbytes/day of uncompressed data	the GCR environment (from solar minimum to solar maximum) and because of the higher probability to measure Solar Particle Events	
		Measure relevant "human" radiation protection quantities as the absorbed dose, the Linear Energy Transfer (LET) spectra and the dose equivalent.					Time resolved absorbed dose rate (1 minute resolution)
How space radiation in lunar orbit can affect the proliferation of specific organism and impact on BLSS in the light of future human exploration?	Investigation of survival and active metabolism in the extreme solar and galactic cosmic radiation environment of space during a biological space exposure mission beyond LEO to the Moon	Measurements of absorbance of all liquid cultures with and without (medium only) organisms	Repeated automatic measurements of temperature (resolution of the measurement) at sample site, frequency 1 x per hour or more	Culturing system + spectrometer	• Closed serializable hardware • Volume of liquid culture: 100 µl (minimum) to 1 ml (optimum). • Minimum of 26 cuvettes • Artificial PAR (photosynthetically active radiation, i.e. light at 400-700 nm) only required for photosynthesising cyanobacteria • Automatic insertion of culture media. A dry air gas headphase with 21 % Oxygen is required • Controlled temperature at 30 °C ± 1 °C • Measurement of Absorbance, at 490 or 600 nm ± 10 nm, expected Absorbance 0.025 to 3, Accuracy 0.03 or better • 4.8W Spectrometer + 2W TC + 1.6W carousel engine +	• Keep the experiment in lunar orbit as long as possible • Expose the instrument to diverse radiation environment	Temperature data for analysis of growth conditions
			Repeated automatic measurements of absorbance of all liquid cultures of life forms and medium only without organisms (negative control) at 490 or 600 nm ± 10 nm, expected Absorbance 0.025 to 3, approximately once or twice per day.				Absorbance data as measure for metabolism, proliferation and effect of radiation exposure with time

					2W Thermal-Control = 10.4W total (maximum including 10% margin and power converter efficiency of 85% considering a feeder of 28VDC) • Spectrometer + On board computer fits in 10 cm3 • Mass budget spectrometer 450g + culturing system 600gr • Data budget of 4.5 Kbyte/frame • No particular pointing is required		

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Additional notes
Curriculum vitae

Loris Franchi was born in Torino, Italy, on October 31, 1990. He attended secondary school at the aeronautical school Galileo Ferraris in Vercelli. After obtaining his diploma, with a thesis about the V2 rocket mission and system design, he started studying aerospace engineering at Politecnico di Torino in September 2014. He obtained his master degree with full marks with a thesis on the topic of control of alkaline fuel cells in collaboration with Thales Alenia Space Torino. In November 2015 he started his PhD research in design methodology for the concurrent engineering approach. During his PhD he participate in important activities in collaboration with the European Space Agency such as workshops and summer school increasing his systems engineering skills. He assisted group of students, teaching practical lectures of *space mission and system design class* at Politecnico di Torino. He was also Team Leader and systems engineer of the Politecnico di Torino CubeSat Team. He founded a start-up named AIKO with the goal of enhancing the autonomy of space missions for which he developed a Artificial Intelligence algorithm for on-board decision making and scheduling.

He is currently looking for his next challenge in his professional life.

List of Publications

- R. Mozzillo, L. Franchi, L. Feruglio, F. Stesina, S. Corpino et al., CubeSat Team of Politecnico di Torino: past, present and future projects, A220, 1° Symposium on space educational Activities, Padova, Italy, 9-12 December 2015
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